eRD14 - EIC PID Consortium
An integrated program for particle identification (PID) for a future Electron-Ion Collider (EIC) detector.

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June 26, 2020

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Abstract

The EIC PID consortium (eRD14) was formed to develop an integrated program for particle identification (PID) for a future Electron-Ion Collider (EIC) detector, for which excellent particle identification is an essential requirement. For instance, identification of hadrons in the final state is needed for understanding how different quark flavors contribute to the properties of hadrons, and reliable identification of the scattered electron is important for covering kinematics where pion backgrounds are large. The PID systems also have the greatest overall impact on the layout of the central detector and put important constraints on the magnetic field. It is thus essential to conduct the relevant PID R&D for the development of a complete EIC detector. In addition to providing solutions addressing the broader EIC requirements, the PID consortium has worked closely with the EIC community to ensure that the R&D projects are compatible with the specific EIC detector concepts that are currently being pursued.

Contents

1 Introduction

The ability to identify hadrons in the final state is a key requirement for the physics program of the EIC. Being able to tag the flavor of the struck quark in semi-inclusive DIS can, for instance, tell us something about the transverse momentum distributions (and potentially orbital angular momentum) of the strange sea, while open charm (with subsequent decays into kaons) is important for probing the distribution of gluons in protons and nuclei. While the distribution of produced particles depends on the specific process, broadly speaking the kinematics for meson production follows the energies of the colliding beams. If the reaction produces a meson traveling in the direction of the proton (ion) beam, this meson can have a momentum which is a significant fraction of that of the beam. If the meson is produced in the opposite (electron) direction, it cannot acquire more momentum than that carried by the electron beam. In the central region it is possible to produce mesons over a wide range of momenta, but the distribution is driven by the kinematics of the process (Q^2, p_T) rather than the energies of the colliding beams[1]. Here, a greater reach of the PID coverage directly translates into, for instance, a larger lever arm in Q^2 — a key goal for the EIC — as well as an ability to probe deeper into the high-p_T region of semi-inclusive DIS. In both cases (high Q^2 and high p_T), the event rates are low, but the physics impact is high. The Q^2 coverage of the detector at central angles (mid rapidity) does, however, grow quickly with the momentum of the detected (and identified) particles. To fully satisfy the physics goals of the EIC, it is thus essential to provide coverage above 5 GeV/c for hadrons (π/K) in the barrel region, with 6–7 GeV/c being ideal. In the electron endcap, one would need to provide hadron ID up to a significant fraction of the electron beam energy ($\sim$ 10 GeV/c), while in the hadron endcap one would need to reach a significant fraction of the proton or ion beam momentum ($\sim$ 50 GeV/c).

To address the different requirements associated with the three different parts of the detector, the consortium is pursuing R&D on (and requesting funding for) three different technologies for imaging Cherenkov detectors: a dual-radiator (gas/aerogel) RICH (dRICH) for the hadron endcap, a high-performance DIRC (hpDIRC) for the central (barrel) region, and a modular aerogel RICH (mRICH) for the electron endcap, which could also be used in the hadron endcap in conjunction with a single-radiator gas RICH such as the one developed by eRD6. A time-of-flight (TOF) measurement, or dE/dx information from a TPC, is also needed for PID in the momentum range below the thresholds of the Cherenkov detectors, for which the consortium has performed R&D on mRPC and MCP-PMT-based TOF systems.

The Cherenkov systems also have a significant potential for e/π identification. When combined with an EM calorimeter, the mRICH and hpDIRC could provide excellent suppression of the low-momentum charged-pion backgrounds, which limit the ability to measure the scattered electron in kinematics where it loses most of its energy (in the detector frame). The progress of the R&D for these systems is very promising, and may in the future eliminate the need for other supplementary e/π identification systems. Further improvement of the e/π capabilities of the mRICH and hpDIRC

[1]Note that p_T is defined with respect to the virtual photon direction in the rest frame of the proton (ion) rather than the beam direction in the detector frame. A large p_T will, generally, give rise to a higher momentum, as well as a larger component transverse to the beam, but the boost smears the distribution.

is thus a natural extension of the current R&D effort. On the hadron side, the dRICH already provides a significant e/π identification capability (10σ at 10 GeV/c, and 3σ close to 20 GeV/c), which is sufficient for the detection of, for instance, decays of charmonium states. An important dRICH study also showed that the performance does not suffer greatly even if the size of the radiator is limited to 1 m.

The PID consortium is also carrying out R&D on photosensors for the Cherenkov detectors. The challenges addressed by the PID consortium are: operations inside the magnetic field of the central detector; and cost reduction. The former is carried out using the high-B test facility at JLab and at the g-2 magnet test facility at ANL, while the latter focuses on adaptation and optimization of LAPPD$^{\mathrm{TM}}$ MCP-PMT's to EIC requirements (pixelated readout, UV photocathodes, high-B capabilities), as well as characterization of early-production sensors.

In FY18 we also started a new effort within the consortium to develop cutting-edge readout electronics for all the small-pixel photosensors (including the LAPPDs) that will be used by the Cherenkov detectors. This work is being led by U. Hawaii and INFN, with support from JLab. Later versions, based on the new HDSoC chip, which is developed under DOE SBIR program by Nalu Scientific in collaboration with University of Hawaii, are intended to form a common readout for all Cherenkov prototypes, as well as the basis for the readout of the final Cherenkov systems to be used the future EIC detector.

Following the EIC R&D Committee recommendations, in FY20 a comprehensive R&D program was initiated to study the potential of SiPM application for Cherenkov detectors at EIC. The program is based on new qualified expertise joining the Consortium. It focuses on temperature treatments and customized readouts (starting with the ALCOR ToT-based chip) to mitigate the SiPM performance degradation expected in the EIC radiation environment. The study is initially associated with the dRICH prototyping, because the dRICH instrumented area location anticipates reduced material budget and radiation tolerance constraints with respect to other proposed detector configurations.

2 Hadron Identification

2.1 PID Requirements and Implementation Options

2.1.1 Hadron ID requirements

The physics program of the EIC, as described in the White Paper, the 2010 INT report, the 2015 NSAC Long Range Plan, and elsewhere, is very broad and multifaceted – and so are the corresponding detector requirements. The most basic particle distribution is that from inclusive Deep Inelastic Scattering (DIS), which essentially sums over all combinations of final-state hadrons for a given kinematics (x, Q^2) of the scattered electron. As one looks at specific subsets of the data, the particle distributions can be quite different. For example, the analysis of events at the exclusive limit leads to transverse spatial imaging of the quarks and gluons in the target nucleon or ion, for which flavor sensitivity is crucial to unravel the chiral-symmetry-breaking structure of the sea. Here, the struck quark hadronizes into a pion or a kaon, taking essentially all of the momentum transferred from the scattered electron. In this subprocess, the kaon momenta are much higher than the average momenta in kaon production in DIS. Similarly, the intermediate case of semi-inclusive DIS allows the creation of transverse images in momentum space. Here it is also important to cover a wide range in meson momentum fraction (*vis a vis* the 'jet'), with PID for flavor separation. Failing to do so will restrict the kinematical reach of the EIC regardless of the beam energies provided by the accelerator.

Another important case to consider is when the kaons are not produced in the primary process, but are decay products of heavier mesons. For instance, the kaons from the decay of the ϕ-meson, which is important for studies of gluon saturation, have higher momenta than kaons from the decay of D-mesons (open charm), which also provide information on gluon distributions.

A compilation of a catalogue of processes and kinematics illustrating the impact of various kaon identification options on the full EIC physics program goes beyond the scope of this R&D proposal. A lot of information can be found in the EIC White Paper, to which we refer. However, we note that for the purpose of understanding the general hadron ID requirements at EIC, this level of detail is not necessary. As long as one keeps in mind that a lot of the information lies in the tails of the distributions, where the number of particles is small, the meson distributions from inclusive DIS provide a good guidance. Figure 1 shows these distributions for pions and kaons in a common kinematics of 10 GeV/c electrons on 100 GeV/c protons, in a broad but typical bin of Q^2.

As discussed in the introduction, with higher beam energies, the meson energies in the endcaps become correspondingly higher, while the distribution in the central barrel, is less affected. Figure 1 clearly shows the need for PID over a very wide momentum range (up to about 50 GeV/c) in the hadron endcap, and a moderate range up to 5 – 7 GeV/c in the central barrel. In the electron endcap, which also sees hadrons with higher momenta produced at lower values of Q^2, the desired range would reach somewhat higher limit than the one suggested by the Q^2-bin shown in Fig. 1, approaching the electron beam energy. Thus, an upper limit of about 10 GeV/c is a reasonable requirement. In addition, we note that the π/K ratios are not excessive – and become smaller for higher momenta, making identification easier. However, while the momentum reach for each system is conventionally quoted at the 3σ level, the analysis of each specific channel can use PID cuts such that the uncertainty from PID would match other uncertainties. Since the curves of separation vs momentum are provided for each system, a user can easily estimate the momentum reach for the level of purity required for their specific channel of interest. It is also worth noting that artificial intelligence (AI) tools have been introduced for the optimization of the dRICH configuration, with preliminary results showing a net improvement in performance. The same tools can also be extended to other systems, making the EIC detector R&D one of the first programs systematically exploiting AI.

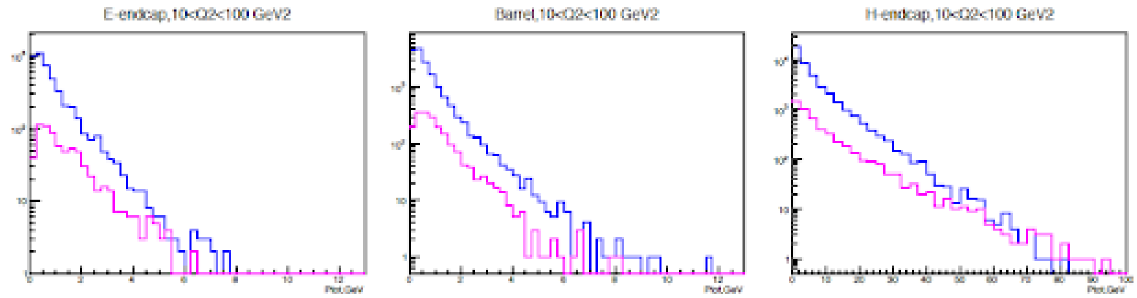

Figure 1: Momentum distributions of pions (blue) and kaons (magenta) from Pythia for DIS events corresponding to collisions between 10 GeV/c electrons and 100 GeV/c protons, a common kinematics of interest, shown for a bin of $10 < Q^2 < 100$ GeV^2 (without imposing cuts related to any specific physics channel or analysis).

2.1.2 An integrated PID Solution for the EIC

The EIC detector concepts that have been developed so far by the EIC community originally had somewhat different layouts of the particle ID systems, but the configurations converged over time to be compatible with the suite of PID systems developed by eRD14. While these concepts continue to evolve as the EIC project progresses, all of them use relatively large solenoids compatible with a TPC-based central tracker. The proposed EIC upgrade of sPHENIX (which would reuse the BaBar solenoid and several subsystems, including the TPC and barrel calorimeters), can thus serve as a representative example. The layout from the 2018 EIC-sPHENIX LOI, shown in Fig. 2, includes the mRICH and hpDIRC from eRD14 and the gas RICH from eRD6 - although it is also compatible with the dRICH from eRD14, which has been the default choice for other concepts.

However, the all-Si central / vertex tracker developed by eRD25 makes it possible to significantly reduce the overall size of the detector and its subsystems, including PID, thereby saving cost without compromising performance. The smaller dimensions also facilitate subsystem integration. Figure 3 shows a new detector concept including the eRD25 tracker and the eRD14 suite of PID detectors (dRICH, mRICH, and hpDIRC). An adaptation of the latter to an all-Si concept is straightforward since there is ample space for the dRICH and there would be fewer hpDIRC bars located closer to the center, neither of which affect the PID performance. Moreover, the mRICH modules are flexible and can be stacked as needed. Thus, although a Si-based concept offers many interesting opportunities, it does not change the required PID R&D effort.

Central Barrel

In addition to meeting the performance requirements, the PID system for the central detector has to cover a large area but with a minimal radial footprint. A DIRC detector offers an attractive solution as it can meet all three requirements. It is the most radially compact PID detector (the radiator bar thickness is less than 2 cm), and the bars can cover a large area while the sensor area remains small. Such a reduction in area can be accomplished in a conventional RICH detector by using mirrors, but this solution is not compatible with the requirement for compactness. Using recent estimates for the cost per unit area, polished fused silica is cheaper than low-cost photosensors, making the DIRC overall more suitable for the barrel than, say, the mRICH. Our ongoing R&D has also shown that performance can be pushed well beyond the 4 GeV/c achieved in BaBar, up to 5 – 6 GeV/c using advanced optics (eRD4) and to 6 – 7 GeV/c by optimizing the system for time-based reconstruction (eRD14), making the hpDIRC a very good match for the EIC requirements. Thus, we have adopted an hpDIRC as a baseline solution, although a high-resolution TOF could also be considered for the PID in the barrel, as it is relatively compact and affordable.

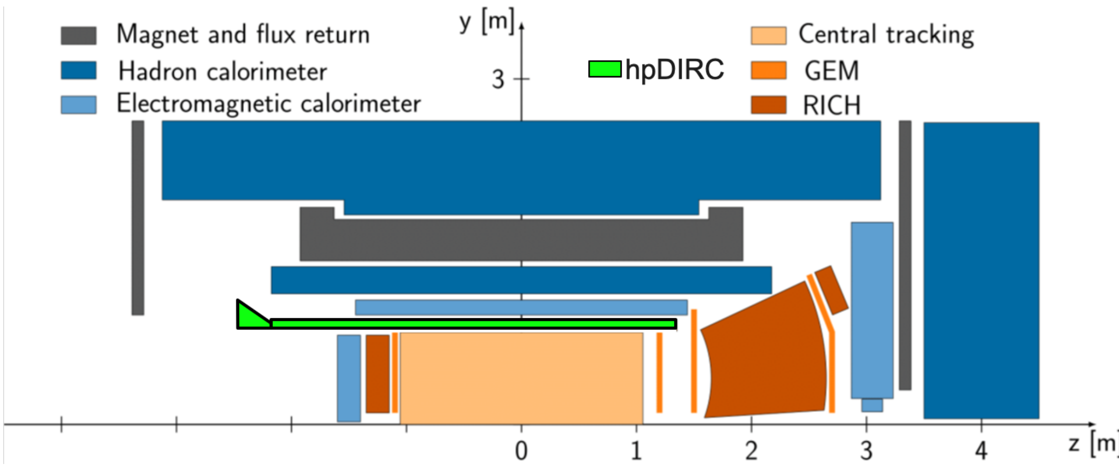

Figure 2: The 2018 version of an EIC detector based on sPHENIX (which uses the BaBar solenoid) includes a hpDIRC at mid-rapidity and the mRICH in the electron endcap. In the hadron endcap, the current concept uses the single-radiator gas RICH developed by eRD6 in combination with the mRICH, but is also compatible with a dual-radiator RICH, such as the one developed by eRD14.

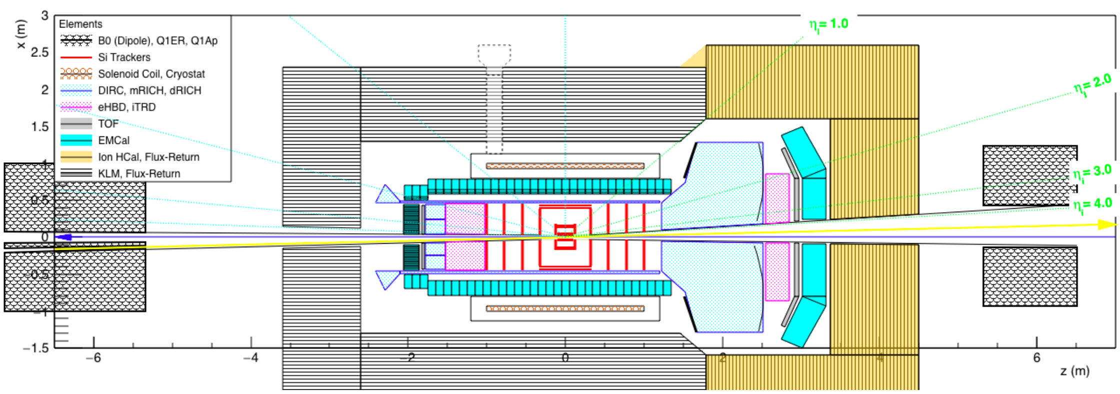

Figure 3: A compact EIC detector using the eRD25 all-Si tracker and the full suite of eRD14 PID detectors (dRICH, mRICH, and hpDIRC).

(Outgoing) electron-side endcap

The EIC is designed to support a wide range of electron beam energies (up to 18 GeV, with a maximum luminosity below 10 GeV). Thus, a compact, high-performance aerogel RICH is a natural choice. In terms of implementation, there are three options. A mirror-based design, a proximity-focused design using two aerogel indices, and a lens-based aerogel RICH. However, the mirror-based option is not compact at all, and the proximity-focused alternative is only compact if the momentum coverage is modest. The lens-focusing mRICH design, on the other hand, offers both a compact design and the desired momentum range. The lens-focusing also reduces the sensor area required per unit of solid angle, which is important since photosensors are the main cost driver of the RICH detectors.

(Outgoing) hadron-side endcap

Due to the large span of hadron momenta, ranging from a few GeV/c to a large fraction of the beam energy (up to 275 GeV/c for protons), the PID requirements on the hadron endcap are in many ways the most demanding. Thus, any future EIC detector will need to incorporate a mirror-based, focusing gas RICH as part of the hadron-side PID solution, with a nominal 3σ π/K coverage up to at least 50 GeV/c.

The key challenge, however, is how to best cover the full momentum range. The most straightforward solution is to have a dual-radiator (gas and aerogel) RICH providing continuous coverage of the full range using one set of photosensors (supplementary coverage by TOF or dE/dx could be useful for the lowest momenta). However, no such RICH has yet been built for a collider experiment with the strong limitations due to space and magnetic field expected for an EIC detector, making the ongoing R&D undertaken by eRD14 imperative. This is achieved by combining n=1.02 aerogel and C_2F_6 or equivalent gas and a layout with sector-based, outward-reflecting mirrors, making it possible to move the photosensors away from the beam. The resulting coverage is shown in Fig. 4.

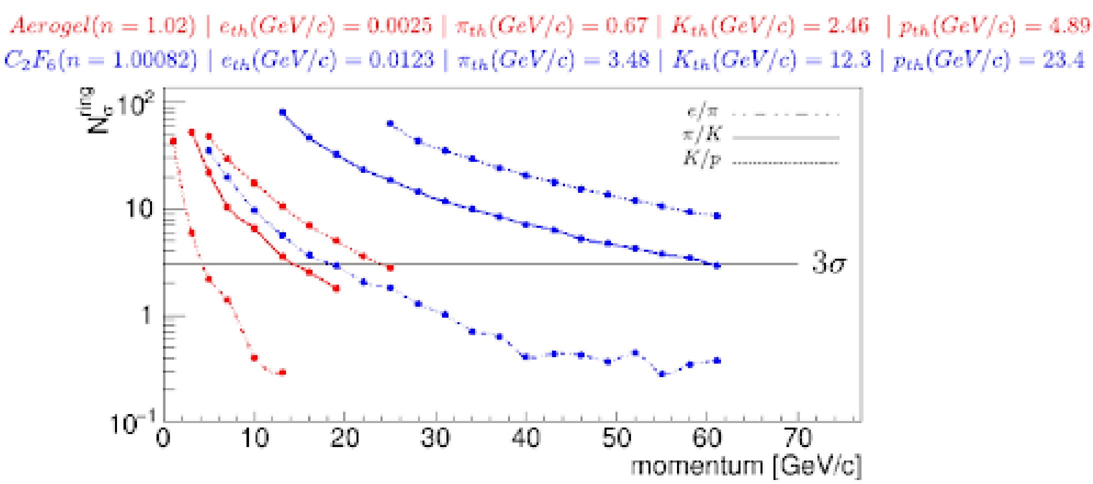

Figure 4: C_2F_6 gas/aerogel dual-radiator RICH performance for a particle scattered at 15°. There is a good overlap between the PID coverage of the aerogel (red) and the gas (blue) for all three pairs of particle species.

2.2 Dual Radiatior RICH (dRICH)

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The dual-radiator Ring Imaging Cherenkov (dRICH) detector is designed to provide continuous full hadron identification (π/K/p separation better than 3 σ apart) from ~3 GeV/c to ~60 GeV/c in the (outgoing) ion-side end cap of the EIC detector. It also offers a remarkable electron and positron identification ($e^{\pm}/\pi$ separation) from few hundred MeV up to about 15 GeV/c. The proposed geometry covers polar angles from $\sim 5°$ up to $25°$. Achieving such a momentum coverage in the ion-side region is a key requirement for the EIC physics program. Currently, the dRICH is, by design, the only hadron identification detector in EIC able to provide continuous coverage in RICH mode over the full momentum range required for the forward endcap.

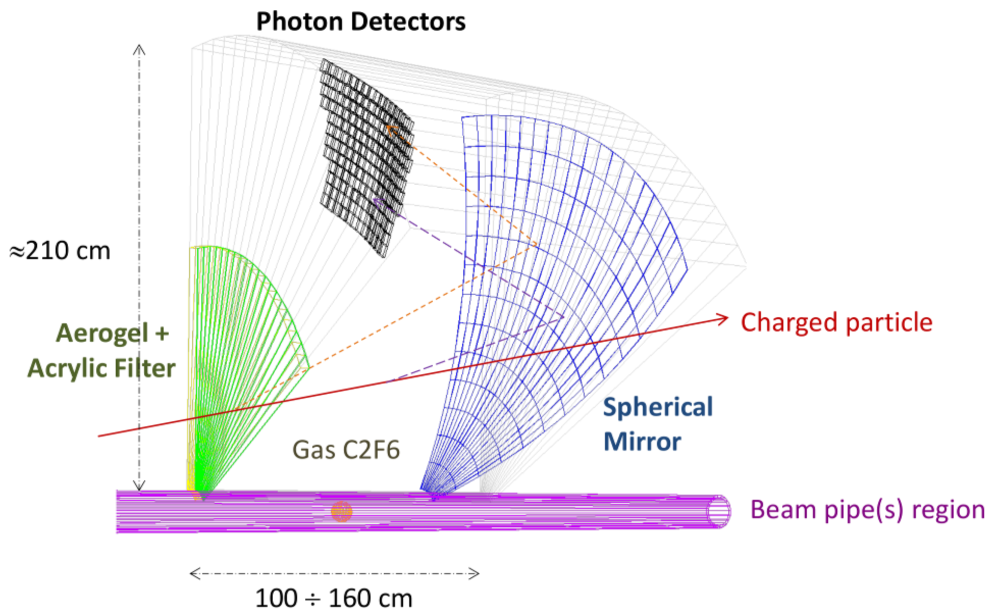

Figure 5: Drawing of one dRICH sector (out of 6): aerogel (yellow), thin acrylic filter (green), C_2F_6 gas filling the volume of the vessel (light gray), spherical mirror (blue) and slightly curved optical sensor surface (black) out of acceptance. The beam pipe region is in pink. A charged particle (red) crosses the detector from left to right and emits two representative photons in aerogel and gas.

2.2.1 Detector Design

The dRICH baseline configuration has been consolidated in the first half of 2018: it consists of 6, identical, open sectors; each sector has two radiators (aerogel and gas) sharing the same outward focusing mirror and instumented area made of highly segmented photosensors (3x3 mm^2 pixels). The photosensors tiles are arranged on a curved surface in a way that minimizes aberrations, as shown in Fig. 5. The dRICH design and performance have been studied through various means: a full Geant4 simulation (including an event based particle reconstruction processor) [2], AI-based learning algorithms with Bayesian optimization to maximize the hadron separation [3], analytic parameterizations taking into account the optical properties of each component or the Geant4 simulated resolutions. When combined with the prototype test results, all theses software tools will be instrumental to optimize the dRICH design and meet the evolving EIC specifications and constraints. The dRICH Monte Carlo simulations used benchmark models with longitudinal (along

[2] L. Barion et al., JINST 15 (2020) 02, C02040.
[3] E. Cisbani et al., JINST 15 (2020) 05, P05009.

beam) thickness of $\sim$ 100 cm and $\sim$ 160 cm, with slightly different optics; the former has been preliminary modeled for the ePHENIX implementation, while the latter has been optimized for the JLab version of the EIC spectrometer. Even the shorter dRICH preliminary version features a performance that fulfills the above mentioned key physics requirements, indicating a remarkable flexibility of possible dRICH configurations. The dRICH focusing system is designed to keep the detector outside the EIC spectrometer acceptance, in a volume with reduced requests in terms of material budget, magnetic field strength, and radiation levels. This feature makes dRICH a natural candidate for the use of SiPMs with an integrated cooling system.

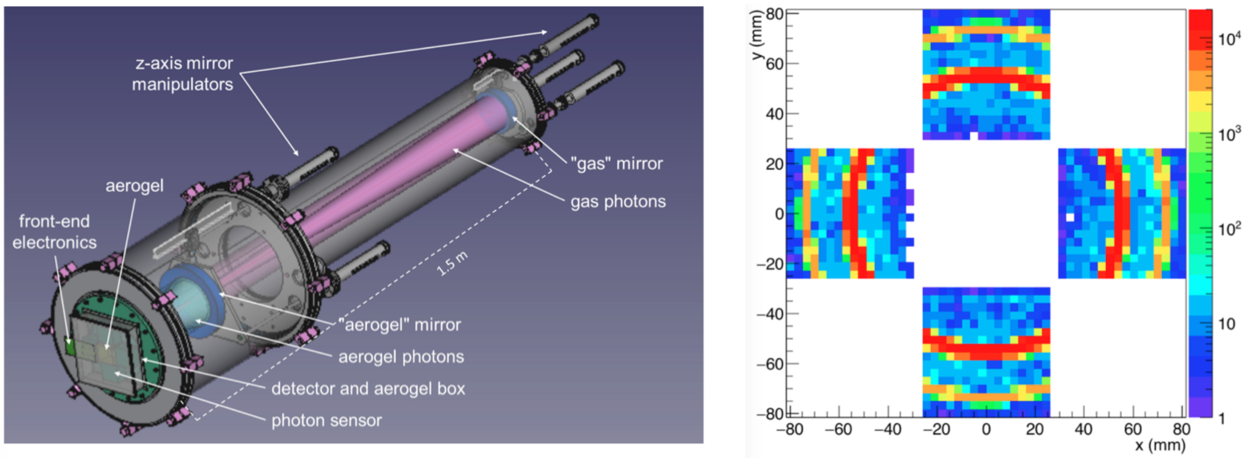

Figure 6: dRICH prototype in the configuration for two radiator imaging (left). Simulated Cherenkov ring generated by the aerogel and gas radiators in a logaritmic scale (right).

2.2.2 dRICH proptotype

A small-scale prototype (1.5 m long) is being developed to investigate critical aspects of the proposed dRICH detector, in particular related to the interplay and long-term performance of the two radiators and the simultaneous imaging. The prototype is designed to be cost-effective and be flexible enough to allow the use and test of different detector and components solutions. A remarkable feature is the ability to image both the aerogel ring (with a cone aperture of 11°) and the gas ring (with a cone aperture of 2.2°) in a limited area. The latter can be instrumented with various sensors, starting with the ones already available within the eRD14 Consortium, e.g., four H13700 multianode PMTs (5x5 cm^2 each) or four S12642-1616PA matrices of 3x3 mm^2 area SiPMs, and related readout electronics.

The prototype vessel is divided into two cylindrical sections to minimize the dimensions while accommodating the different Cherenkov paths, see left panel of Fig. 6. The elements of the vessel are made of vacuum standards, to allow an efficient and safe gas exchange or pressure tuning for different gases. The entrance flange houses a UV-transparent lucite foil (or quartz window) to isolate the inner gas volume from the external dark box housing various sensors and an aerogel tile with possible additional UV filters. The mirrors can be rotated for alignment and translated to adjust the focal plane position by means of manipulators. Depending on the position of the central mirror, the performance of each single radiator can be studied in detail without interference, or the two radiators can work together to create a realistic occupancy in the limited instrumented area, see right panel fog Fig. 6. The present configuration of the sensors guarantees the best coverage of the gas ring (radius of $\approx$ 6 cm). The photo-sensor pixel size of 3x3 mm^2 will keep the angular digitization (or pixel) error comparable to the other errors, allowing for the assessment of the intrinsic sources of uncertainties of the various radiators.

The prototype is instrumental to validate the dual radiator approach to cover the momentum range of few GeV/c – multi tens of GeV/c . A test-beam is planned in summer 2021 at the Fermilab test-beam facility, using GEM tracking stations and a gas purging system borrowed from Stony Brook. As backup solution, a test-beam at the CERN PS test-beam facility is under consideration. The study of the response at meson beam momenta intermediate between the two radiators working ranges is of particular interest.

The goal of the present activity if to complete the dRICH prototype in its baseline configuration, and perform a first test-beam in summer 2021 to validate the dual-radiator working principles with the reference sensors and MAROC3 readout.

2.2.3 SiPM program

The INFN involvement has been strengthened as a consequence of the two R&D recommendations:

In-depth EIC R&D Review Report (11/25/2019): *"An important remaining issue is the SiPM noise rate after irradiation which should be clarified. We expect that it will take 2-3 years to fully understand if SiPMs can be used in RICH detectors at EIC".*

18th EIC R&D Meeting Report (01/30/2020): *"The committee again recommends the group to re-examine options that do not rely on waveform sampling, e.g., a TOT-based design like the TOPFET2 ASIC, which is radiation hard, has low power consumption and has achieved a very good resolution per single photon with SiPMs."*

These goals require specialized expertise and a long-term planning. Six INFN units (BO, FE, CT, LNF, RM1, TO) have initiated a collaboration to study the potential of SiPM sensors for Cherenkov applications [4] [5] at EIC. In connection with the eRD14 activity, so far only partial studies have been done on SiPM usage for Cherenkov imaging prior of irradiation, and on SiPM photon counting capability post irradiation. The new INFN units that intend to join the PID Consortium have recognized capability in front-end chip development and cryogenic SiPM detector realization, having been involved in the TOFPET development, COMPASS RICH readout, ALICE TOF readout (based on NINO and HPTDC) and the DARKSIDE SiPM cryogenic detector. The enriched expertise is essential for a systematic and complete irradiation program, and the validation of the usage of irradiated SiPM for imaging in realistic EIC conditions. The complete program assumes a 2-3 years R&D activity in preparation of the dRICH TDR. A plan has been defined for the first year (FY21) to reach a first assessment of the use of irradiated SiPM in conjunction with the dRICH prototype, as detailed in the following.

[4] E. Garutti and Y. Musienko, Nucl. Instrum. Meth. A 926 (2019) 69.

[5] S. Korpar and P. Križan, Nucl. Instrum. Meth. A 970 (2020) 163804.

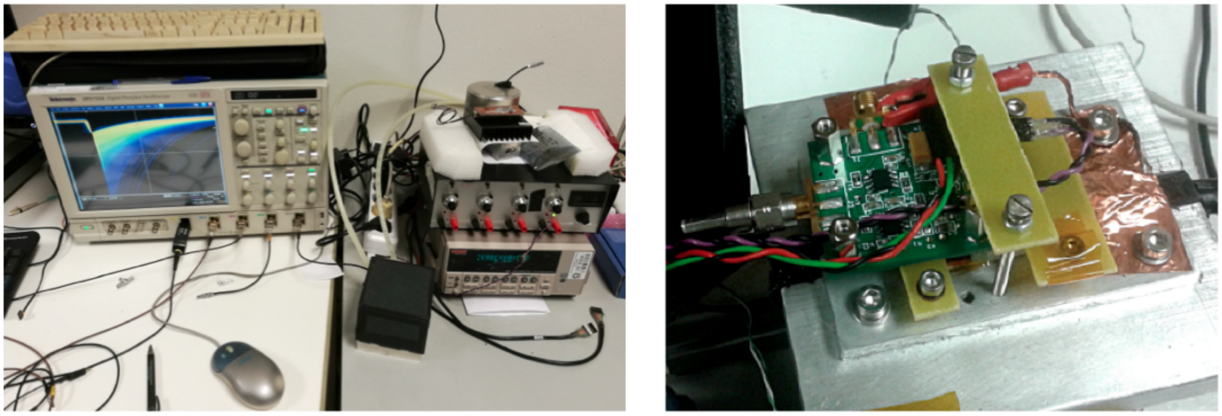

Figure 7: Test bench for the characterization of irradiated SiPM. Instruments for the I-V curve measuremnt and the dark count signal sampling (left), preamplification and cooling stage for a SIPM sensor (right).

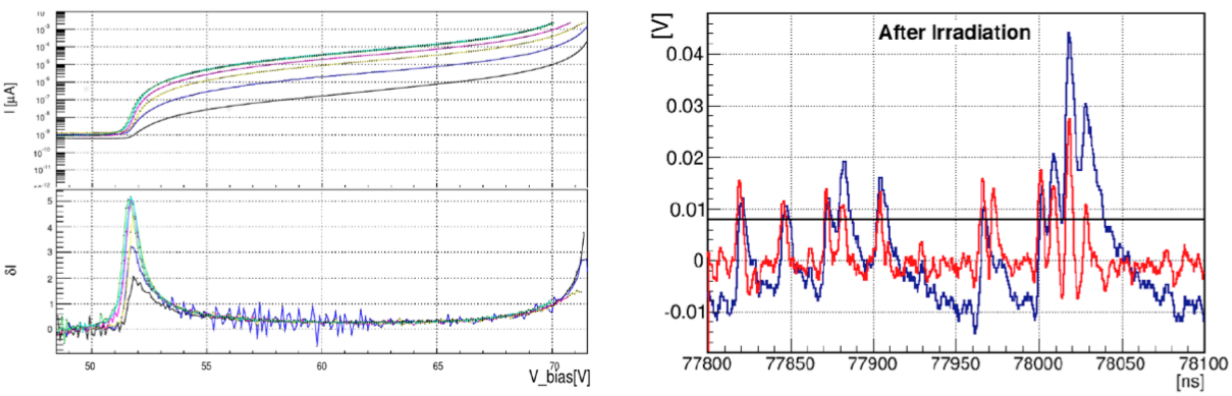

Figure 8: Analysis examples of the irradiated SiPM signals. The I-V curve and its derivative defines the breakdown voltage and the over-voltage working interval as a funciton of the intergrated n_{eq} dose (left). The offline software filter restores a proper baseline and correctly discriminates signals close in time (rigth). The horizontal line indicats a possible threshold level.

A survey is currently in progress to select suitable candidates among industrial partners as Hamamatsu, OnSemiconductor and Ketek, as well as more customized products developed by Fondazione Bruno Kessler, which has a cooperation agreement with INFN. The effect of radiation damages (and the capacity to recover through a controlled annealing cycle) as a function of the SPAD cell-pitch will be in particular investigated. Up to three manufacturers and two sensor types per manufacturer will be selected. The sensors will be arranged in carrier boards mounting 32 SiPMs in a 4x8 matrix array. One carrier per manufacturer will be irradiated at various integrated doses (0, 10^9, 10^{10}, 10^{11} n_{eq}/cm^{-1}) and will undergo the controlled annealing cycles at high temperature (up to 180 C), while the other will be preserved as a reference. The SiPM irradiation will be conducted at the "Centro di Protonterapia" in Trento, Italy, where INFN TIFPA operates an irradiation facility that provides proton beams up to 200 MeV energy, with variable beam spot

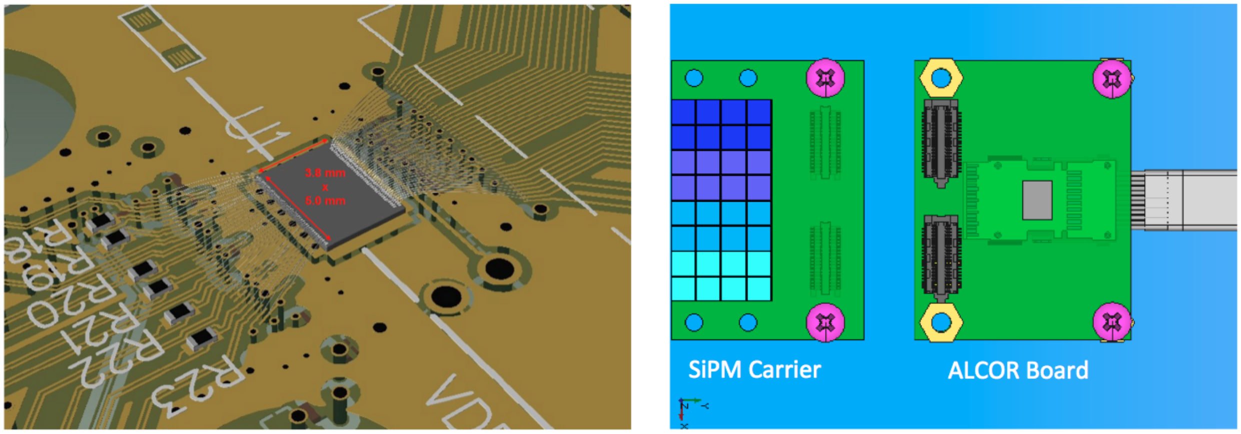

Figure 9: 3D rendering of the ALCOR chip wire-bonded on the evaluation board (left). Draw of the SiPM carrier board (color of SiPM corresponds to radiation dose) and the ALCOR readout board (rigth).

size [6]. Such collimated beam can be used to irradiate specific areas of the SiPM matrix at the wanted equivalent 1 MeV neutron dose, while an active readout monitors online the performance degradation. The annealing cycles and low-temperature characterization will be conducted with a climatic chamber, already available at INFN, able to run from $-40°$ up to $180°$.

The matrices will be characterized following a protocol derived from previous irradiation tests [7]. The typical measurements are: I-V characteristic curve by means of a Keithley 6487 pico-amperometer; SiPM dark count signal sampling at 2.5 Gb/s over a 20 ms time window by a Tektronik DOP 7254 oscilloscope, see Fig. 7. The first allows to define the breakdown voltage and the overv-oltage working interval. The second, in conjunction with an offline software filter to reduce the slow recharge tail of the SiPM signal and restore a proper baseline (pedestal), allows to evaluate the post-irradiation photon counting capability, see Fig. 8. The single-photon response will be studied with the pico-second pulsed laser stations in developement for the electronics characterization, see Sec. 4.3. Such measurements will be done at various stages of the program to define the baseline performance of each sensor and its dependence on temperature, irradiation dose and annealing cycle.

The irradiated SiPM imaging potential will be studied with a customized ToT-based electronics. The ALCOR (a low power chip for Optical Sensor Readout) chip prototype is a first test vehicle for a high-rate digitisation backend for SiPM readout in fast timing applications. It is a 32-channel ASIC that features signal amplification, conditioning and digitisation, see left panel of Fig. 9. It features low-power TDCs that provide single-photon tagging with time binning down to 50 ps and is designed to work at cryogenic temperatures. The design of a system-grade ASIC targeting the dRICH specifications is now being pursued by the design group at INFN. The ALCOR chip is based on a triggerless time-based (time-of-arrival and time-over-threshold) readout and features a SEU-

[6]F. Tommasino et al., Physica Medica 58 (2019) 99-106, DOI:https://doi.org/10.1016/j.ejmp.2019.02.001.
[7]I. Balossino et al., Nucl. Instrum. Meth. A 876 (2017) 89-92, DOI:https://doi.org/10.1103/PhysRevC.98.015207.

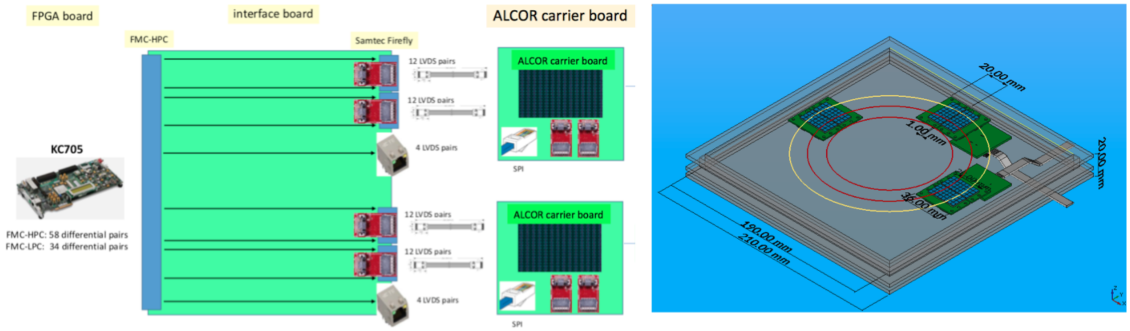

Figure 10: ALCOR readout scheme for irradiated SiPM imaging where a KC705 FPGA board connnects up to six ALCOR readouts (left). Six SiPM carrier boards arranged in the dRICH detector box for imaging tests (right). The ALCOR front-end electronics is more compact than the MAROC boards, and Firefly cables route the digitized signals to the external DAQ FPGA.

protected logic. A dedicated design of the front-end shall allow for count rates well exceeding 500 kHz per channel. The chip architecture and matrix floor-plan will allow for a future version to be assembled chip-on-board with bump-bonding (the first prototype uses wire-bonding padframes), which will be an enabling factor for the design of very compact and robust front-end electronic boards. ALCOR can be seen as an in-house evolution of the MAROC discriminating approach as alternative to the high-frequency sampling, in line with the R&D Committee recommendations. As a backup solution, the group will consider the use of a commercially available chip featuring similar specifications, such as the TOFPET [8] or TOFPET2 [9]. The thermal contact for cooling and customized decoupling circuits (high pass filter) for possible signal pre-conditioning are mounted on the SiPM carrier board, see right panel of Fig. 9. This configuration allows the use of the same ALCOR readout board for any SiPM device in various experimental conditions. During the irradiation tests and sensor characterization in the climatic chamber, the ALCOR readout can be used as complementary addition to the commercial instrumentation described above. The ALICE TOF readout based on NINO chip and the CLAS12 RICH readout based on MAROC3 can be used as a benchmark for the post-irradiation performance characteriztion. Up to six ALCOR boards can be readout by a Xilinx Kintex-7 FPGA KC705 Evaluation Kit, see Fig. 10, to instrument an area suitable for imaging tests with the dRICH prototype and operate an already remarkable selection of SiPM, up to two types for three manufacturers. The irradiated (and preserved) sensors will be cooled down to the working temperature (down to $-40°$) by means of Peltier cells, a technique successfully employed during the mRICH beam test. The aluminum base of the detector box is designed to provide a good thermal contact with the Peltier cells while being cooled by an external chiller to provide heat removal.

The goal of the present activity if to realize the SiPM carrier in time for the irradiation tests in winter 2020, perform characterization and annealing treatments in spring 2020, and a imaging test in conjunction with the ALCOR readout during the dRICH test-beam in summer 2020.

[8] M.D. Rolo et al., 2013 JINST 8 C02050
[9] R. Bugalho et al., 2019 JINST 14 P03029

2.2.4 Synergies and Investments

The dRICH prototype and SiPM program are exploiting the synergies with the Consortium and eRD initiatives. Test-bench facilities and readout infrastructure derived from CLAS12 RICH are going to be maintained and used for radiators and sensor characterizations. The investigation of various gas performance and magnetic field tolerant sensors (SiPM) are instrumental also for the only-gas RICH approach. The photosensors and DAQ are shared between the dRICH and mRICH prototypes. The INFN manpower assigned to the dRICH prototype realization and SiPM program will also contribute to the mRICH and electronics working packages. This opens the possibility to test the readout solutions with various detectors and configurations at a reduced cost. In particular it would allow a detailed comparison of the performance between mature technologies (multi-anode photo-multipliers and MAROC readout) with innovative solutions (SiPM matrices with ALCOR and SiREAD readout) and investigate the complementarity of the sampling and discriminating readout architectures in conjunction with a trigerless approach.

Ongoing INFN collaborations with CERN and TIFPA facilitate the organization of beam tests in Europe, while the INFN collaboration with JLab and Fermilab laboratories facilitate test-beams in USA. In the case of Fermilab, a preliminary agreement with Stony Brook has been formulated to borrow their gas purging and GEM tracking systems. Contributions to the EIC background study (in coordination with eRD21) has been planned to verify the benchmark n_{eq} fluence level taken as representative of few year at full EIC luminosity, now estimated in $10^{11}\, n_{eq}/cm^2$. Collaboration with eRD1 has been planned for the study of SiPM tolerance to radiation.

INFN in-kind contributions accounts for salary of staff personnel, infrastructures in Italy, collaboration with EU Institutes and part of the components. It is expected that INFN will cover the costs of the dRICH prototype mechanics and optical components, and the aerogel and gas radiators for the tests planned in Europe. INFN will also cover the cost of the SiPM irradiation tests, the initial adaptation and tests of the ALCOR electronics with the dRICH SiPM, the DAQ electronics and integrated cooling system, so no corresponding funding to the R&D program is requested for FY21.

The budget for the proposed activity consists in the contribution for manpower (46 k$), travel (6 k$) and transportation (4 k$) costs for the test-beams, gas radiators and comsumable materials for the test in USA (10 k$), and realization of the SiPM carrier boards, e.g. part of the sensors and the relative front-end electronics (8 k$).

2.2.5 FY21 Proposed dRICH R&D Activities

1. Complete the baseline version of the prototype.
2. Perform a first SiPM irradiation campaign.
3. Study potential temperature treatments of the irradiated SiPM.
4. Perform a test beam with the reference readout to verify prototype functionality.

5. Use the prototype to perform imaging tests with the irradiated SiPM.
6. Validate the Monte Carlo simulation based on GEMC.
7. Improve dRICH model based on the test results and re-estimate expected performances (tune relevant parameters used in the Monte Carlo to carry on the past years analysis/development and consolidate the performances of the proposed detectors).

2.2.6 FY21 dRICH R&D Deliverables

1. Realization of the dRICH prototype baseline version.
2. Irradiation campaign of a selection of SiPMs.
3. Prototype beam test with reference readout.
4. Imaging tests with irradiated SiPM.
5. Assessment of the aerogel/gas interplay.

2.3 Modular Aerogel RICH (mRICH)

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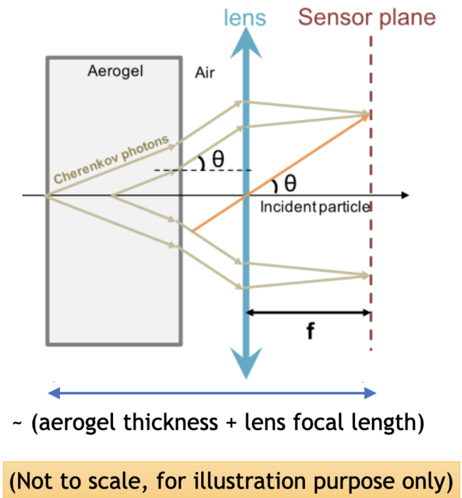
The design goal of mRICH is to meet the EIC physics requirements for K/π separation in momentum range from 3 to 10 GeV/c and the physical constraints of the EIC experiments. It also provides excellent e/π for momentum below 2 GeV/c.

The novel design of mRICH consists of four components. A block of aerogel serves as the Cherenkov radiator. Immediately followed by an acrylic Fresnel lens, which focuses the ring image and acts as a UV filter. A pixelated optical sensor is located in the image plane, and the gap between the lens and the image plane is bounded by four flat mirrors. Figure 11 (left) shows the working principle of mRICH. Also shown in Fig. 11 (right) is an mRICH event display of a 5 GeV/c pion from a realistic GEANT4 simulation.

The working principles of mRICH have been tested and verified at the Fermilab test beam facility. The first mRICH prototype was constructed in 2015 and was successfully tested at Fermilab in 2016. The results from the first beam test have been published in NIM A (2017). An improved mRICH prototype was developed in 2017 with a longer Fresnel focal length ($f = 6''$) and a new holder box made of aluminum plates for the mRICH optical component as shown in Fig. 12. The second mRICH beam test was performed in 2018 with the new prototype and new photosensors of smaller pixel size (Hamamatsu H13700, 3 mm $\times$ 3 mm) in comparison with the sensors (6 mm $\times$ 6 mm) used in the first test. Most of the mRICH related R&D progress and the project activities in the coming year are centered around the second mRICH prototype.



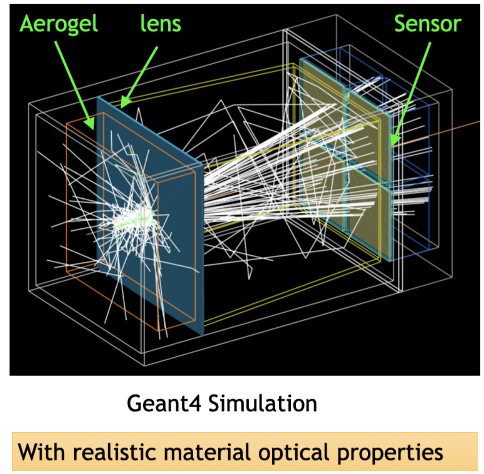
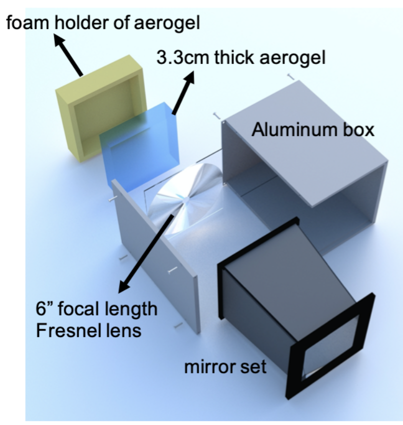


Figure 11: Left: Ray tracing diagram of mRICH design principle. Right: simulated detector construction and an event display from a 5 GeV/c pion.



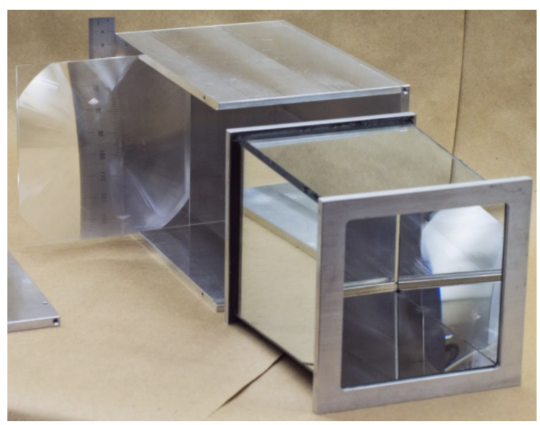


Figure 12: The second mRICH prototype design 3D rendering (left) and the partial detector assembly (right). Optical components only are shown.

2.3.1 FY21 Proposed mRICH R&D Activities

The activities we propose for FY21, include the following:

- mRICH beam test at JLab (using 1 to 6 GeV/c secondary electron beam) with tracking capabilities. This is an essential measurement for the demonstration of the mRICH performance, specifically the $e\pi$ and πK separation. In the test, the mRICH prototype will be read out by four MaPMTs (pucrhased in previous fiscal years), using the MAROC-based readout and JLab data acquisition that were developed and demonstrated previously. The logistics, manpower, negotiations, and implementation of the test setup to run parasitically in Hall D have been already established. The test will take place during the eight-weeks of beam time that are currently on schedule at JLab in summer 2021. This is a low-risk activity with substantial benefits and moderate cost.

- Continuation of the analysis of data from the 2nd mRICH beam test.

- Simulation study of an mRICH array in the context of ePHENIX. The goal of the study is to quantify acceptance and efficiency with and without projectivity requirements.
- Development of an optical characterization system to measure the lens and aerogel block properties (students project at GSU funded by internal sources).
- Participation in a joint beam test at FNAL with the LAPPD group. The main objective of this activity is to test the viability of using Gen-II LAPPDs with an external, pixelated readout board for EIC RICH detectors. In the test, Gen-II LAPPDs will be used to readout one mRICH prototype unit exposed to a proton beam. The Gen-II LAPPD provides for only a stripline direct readout, which does not satisfy the requirements of the EIC-PID Cherenkov detectors for a pixelation with a small pixel size. At the same time, it has a a lower cost than the pixelated GEN-III LAPPD. As part of the eRD14 effort on adapting the LAPPDs for EIC-PID aplications, the ANL group has shown that a capacitive readout via an external pixelated board yields a position resolution of 1 mm, which is promising for the EIC RICH application. The demonstration that such a configuration can provide the required RICH performance is a critical aspect of the sensor assessment we need for the TDR. This assessment will serve also the dRICH efforts. For more details on the LAPPD test-beam program, see section 4.2.

2.3.2 FY21 mRICH R&D Deliverables

- Publication of the results of the second beam test of the mRICH prototype.
- Carry out the third mRICH beam tests (at JLab and Fermilab).
- Report on the results of mRICH array simulation studies in the sPHENIX forward and backward rapidity regions using Fun4All framework.

2.4 High-Performance DIRC (hpDIRC)

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A radially-compact detector based on the DIRC (Detection of Internally Reflected Cherenkov light) principle, shown schematically in Fig. 13a, is a very attractive solution for the EIC detector, providing particle identification (e/π, π/K, K/p) over a wide momentum range. The DIRC detector is a special type of RICH counter using rectangular-shaped radiators made of synthetic fused silica that are utilized also as light guides to transport Cherenkov photons to an expansion volume, where the photons are recorded by an array of photon sensors. During the photon transport, the emission angle of Cherenkov photons with respect to the particle track is maintained and can be reconstructed from the measured 3D parameters: the image location on the detector surface (x, y) and the time of arrival of each photon (t).

2.4.1 Summary

The objective of the DIRC R&D undertaken by the EIC PID consortium is to extend the PID capabilities of DIRC counters well beyond the state-of-the-art (*e.g.*, Belle-II and PANDA). The past

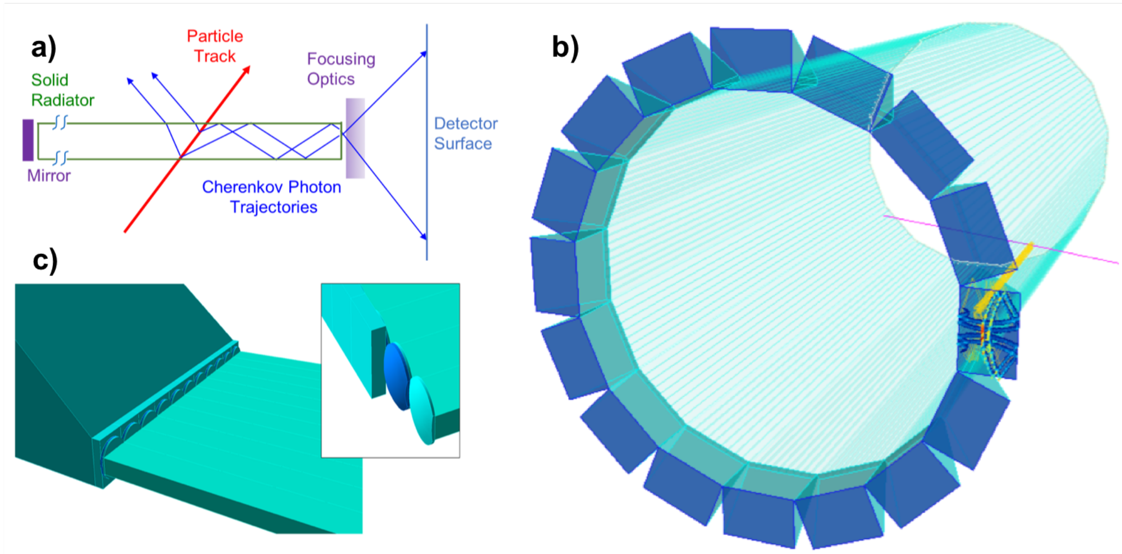

Figure 13: a) Schematic of the DIRC principle. b) Geant4 geometry for the simulation of the High-Performance DIRC where one can see the accumulated Cherenkov photon hit pattern for charged kaons. c) The fused silica prism expansion volume, a row of spherical three-layer lenses with high index of refraction (no air gaps) and the radiator bars. The insert shows the individual lenses and layers of the spherical lens system.

R&D activities funded by this program (initially eRD4, later eRD14) demonstrated the feasibility of a high-performance DIRC (hpDIRC) to provide 3σ separation of π/K up to 6 GeV/c, e/K up to 6 GeV/c, e/π up to at least 1 GeV/c, and K/p up to 10 GeV/c. The implementation of the hpDIRC into a Geant4 simulation is shown in Fig. 13b. Key elements in achieving this performance are innovative focusing optics (shown in Fig. 13c) and a time-based reconstruction algorithm. The ultimate goal of the ongoing program is to demonstrate this performance in a test beam with a prototype that is representative of the intended EIC hpDIRC configuration (small-pixel photosensors, high-resolution timing, advanced optics, *etc.*). Milestones towards achieving this goal include the design, characterization, and validation of a radiation-hard lens as well as the detailed simulation of the hpDIRC design and the development of the reconstruction algorithms. The last phase of the project will involve the validation of the simulated performance of the high-performance DIRC design with the full system prototype in particle beams.

In the past fiscal year our major activities were: (1) Completion of the PANDA Barrel DIRC prototype transfer to U.S.; (2) a detailed radiation hardness study of candidate lens materials, including PbF_2 and sapphire, using both neutron and gamma sources; (3) the upgrade of the laser setup to validate the optical properties of the prototype lenses; (4) restarting the simulation studies with a focus on preparing and setting up the environment for the quantitative studies of the alternative design options as well as the hpDIRC prototype.

In spite of the difficult time for travel and the operation of labs and universities, we were able to significantly expand the expertise and workforce of the EIC DIRC group. Dr. Albert

Lehman, a detector specialist and MCP-PMT expert from Erlangen University in Germany, has joined the consortium to support the hpDIRC sensor evaluation task and provide advice for the hpDIRC prototype validation at Stony Brook and beam test campaign at FermiLab. Dr. Maria Patsyuk, a DIRC expert from the Joint Institute for Nuclear Research in Russia, was hired as a temporary consultant. Dr. Patsyuk has a broad range of DIRC experience from working on the PANDA Barrel DIRC and the GlueX DIRC as one of the core developers of the simulation and reconstruction software. She will take over several hpDIRC simulation workpackages and help bring our new PostDoc up to speed. Dr. Nilanga Wickramaarachchi, recently graduated from ODU university, was hired as a Postdoctoral researcher at CUA. His first responsibility on the hpDIRC project will be on the hpDIRC and prototype simulation. Once the current restrictions on travel and lab operations are lifted, he will continue his work on DIRC simulations but will also support ongoing hardware activities, like the lens evaluation and radiation hardness studies. He will also be crucial for the prototype activities in terms of both software and hardware.

The EIC DIRC R&D program continues to benefit greatly from the synergy with the PANDA DIRC R&D program, which has involved know-how, hardware, and software contributions. A key component of the EIC DIRC R&D program is taking advantage of the transfer of the PANDA Barrel DIRC prototype to the U.S., which reflects the long-term interest of the GSI DIRC group to remain involved in the EIC project.

2.4.2 Synergetic Activities Supported by External Funding

The synergy with the PANDA Barrel DIRC project not only provided access to the prototype and the CERN test beams in 2015, 2016, 2017, and 2018 but includes several planned mid- and long-term contributions from the GSI DIRC group to the EIC DIRC project. With the submission of the PANDA Barrel DIRC TDR in 2017 the activity focus of the GSI DIRC group on PANDA shifted to the mechanical design and the component construction, including the bar box assembly. Both activities are directly relevant to the EIC DIRC.

After conclusion of the beam tests of the PANDA Barrel DIRC, some of the components of the prototype have become available for use by the EIC DIRC effort on the basis of a long-term loan or an in-kind contribution. The mechanical prototype structure, as well as at least one narrow bar, one wide plate, one prism expansion volume, a set of PHOTONIS XP85012 MCP-PMTs and PADIWA/TRB readout electronics for initial tests, are in a process of being transported to the U.S. for future prototype beam tests at Fermilab or BNL. This will significantly reduce the financial investment required to set up the first prototype for the test of lenses, sensors, and readout electronics with particle beams (this would be a deliverable in FY22/FY23). This activity in progress with the goal of completing the transfer in FY20.

2.4.3 Proposed hpDIRC R&D Activities

In FY21 we will conclude two long-time activities connected to the development of the radiation hard 3-layer lens, a crucial component of the hpDIRC detector. A test of the sensitivity of the leading candidates for the middle layer of the hpDIRC lens system to neutron radiation and a combination of neutron and gamma radiation is scheduled for the summer of 2020. Following the analysis of the data we expect to write up the results in a journal publication. Three of the tested materials were used in several lens prototypes and their focusing properties will be measured in the newly upgraded laser setup at ODU. Results from the measurements will described in a journal publication.

After the successful transfer of the PANDA DIRC prototype components to the U.S. the hardware focus of the program will shift towards preparing the full-system hpDIRC prototype. A lot of effort will have to go towards developing a working combination of small pixel sensors and a fast readout system to match the required timing precision. To this end we plan to procure two commercial MCP-PMTs with small pixels, combine them with the readout electronics developed within this consortium, and test the complete readout units with a picosecond laser pulser in the DIRC lab at Stony Brook.

Dr Wickramaarachchi will be responsible for the prototype simulation and reconstruction as well as the commissioning of the prototype readout electronics and DAQ. He will also study of the beam instrumentation requirements for the FermiLab beamline. In the future he is expected to lead the analysis of the prototype data. The experience from the prototype simulation will be applied to improve the current hpDIRC design.

Following the initial generic hpDIRC design implementation, it is now important to study in detail the effect of different bar sizes, focusing system options, expansion volume shapes and dimensions, as well as sensor types (MCP-PMTs vs. SiPMs) and different pixel sizes on the DIRC performance to identify a credible and cost-efficient baseline design for the hpDIRC. The implementation of the initial design in the full EIC central detector simulation framework already started and will be an important step to facilitate the study of the combined PID performance of the eRD14 detector systems, one of the key deliverables of this consortium.

The performance of the budget fDIRC option (reusing the legacy BaBar DIRC bar boxes) and the ultimate DIRC (combining narrow bars and plates within one sector) will be compared to two other versions of the hpDIRC design (narrow bars or wide plates).

Incremental hpDIRC Prototype Development The preparation of the hpDIRC prototype will require further development of the simulation software to work out details of the prototype as well as the implementation of the beam test environment in Fermilab.

The shipped components of the prototype will have to be tested before being reassembled. This will include the validation of the readout electronics and DAQ system using a picosecond laser pulser as light source, still using the PANDA components, including the Photonis XP85012 MCP-PMTs with the larger 6.5mm pixel pitch. In the next step we plan to add two MCP-PMTs with 3 mm $\times$ 3 mm pixels, coupled to readout electronics currently being developed as a consortium activity in Hawaii, and validate the performance.

Once the hpDIRC prototype is validated in the lab it is ready for the first beam test at Fermilab, expected in early 2022. The first milestone will be to reproduce the PANDA Barrel DIRC results from the CERN beam tests in a reference measurement, using the PANDA optics and XP85012 MCP-PMTs (with 6.5mm pixel pitch). If possible, beam data will be taken with the small-pixel MCP-PMTs as well and compared to the results from the larger pixels.

The ultimate goal is to assemble an EIC DIRC prototype with proper pixel-size sensors and readout electronics to validate the simulated performance and to directly measure the PID performance with a mixed hadron beam.

Development of the LAPPD sensors and readout is well aligned with the hpDIRC prototype timeline. Availability of the 32x32 channel version of the Gen III HRPPD will be crucial to start work on the readout electronics prior to the assembly of the complete prototype for the second beam test campaign, expected in 2023.

Even before such a small-pixel LAPPD sensor is available, the the development of readout electronics and the validation of the prototype will require the procurement of a sensor with small pixels. The only commercially available MCP-PMT candidates with pixels sizes of 3 mm or less are the PHOTONIS XP85122-S (with a pixel pitch of 1.6 mm, to be grouped into 3.2 mm pixels) and the Photek MAPMT 253 (with a pixel pitch of 3.5 mm). Given the current funding situation, we previously decided to prioritize the lens and software development for FY20 and postponed the sensor procurement. However, with a clear plan for the hpDIRC prototype in place, the procurement of the sensor is the main hardware priority in FY21.

One additional small-pixel sensor will be procured through the High-B sensor-evaluation program, intended for a detailed characterization of the gain, timing resolution, and ion-feedback rate at JLab in summer of FY21. It will then be sent to the Hawaii electronics group for validation of the fast readout electronics. The availability of the sensor in FY21 has another timely benefit, which is the possibility to compare in detail its timing and charge-sharing/crosstalk properties to those of the newly developed LAPPDs. The comparison between the performance of various photon sensors that are viable candidates for the EIC-PID detectors is an important aspect of the program carried out by the EIC-PID consortium.

Characterization of the Radiation-Hard 3-Layer Lens Prototypes The production of a radiation hard 3-layer lens is an essential step for the hpDIRC R&D process. Several new prototype lenses were recently procured by CUA and GSI, including two lenses with the middle layers made of PbF_2 and sapphire, funded by this program. The optical performance of all prototype lenses will be evaluated in the laser setup at ODU for 3D mapping of focal plane, upgraded in FY20 to improve the precision and completeness of the measurement. The goal is to complete the measurements in FY21 with a journal publication describing the study of the various prototype lenses in detail.

In parallel to this activity we are testing the optical materials in terms of radiation hardness. The determination of the radiation hardness of materials is an important aspect of the EIC DIRC R&D. Synthetic fused silica, which is used for most of the optical components in all DIRC systems, was already extensively tested for the BaBar and PANDA DIRC counters and proved to be radiation hard. However, the middle layer of the 3-layer lens was made, in early prototypes, of a high-refractive index lanthanum crown glass (NLaK33, S-YGH51 or S-LAH97), and our radiation tests showed that this material may not be suitable for the final design. We studied several materials as potential alternatives to lanthanum glasses, and sapphire and PbF_2 are the leading candidates.

In FY21 we will conclude the analysis of the data from the gamma and neutron irradiation runs of the lens materials, for doses well beyond those predicted for EIC, to clearly identify the most suitable material for the middle layer of the hpDIRC lens system.

<u>e/π **Separation**</u> In early 2020, the "Yellow Report" activity was launched to define the requirements for the different EIC detector systems. This consortium has invested a significant amount of work into this effort. A particular focus was on the potential of the eRD14 detectors to contribute to the e/π identification at lower momentum, as required for EIC physics. It is expected that the supplementary e/π performance will become an important criterion in the selection of the PID technologies in the final detector. To address this issue in a timely way we started the study the e/π performance of the generic hpDIRC design in FY20. The goal is to replace the naive e/π separation power estimate, shown in previous proposals, which was calculated using the simulated Cherenkov angle resolution 6 GeV/c and the expected Cherenkov angle difference of electrons and pions as a function of momentum (ignoring the effect of multiple scattering). By using the full Geant4 hpDIRC simulation the effects of multiple scattering and the expected angular tracking resolution, which dominate the hpDIRC performance at low momentum, can be studied separately.

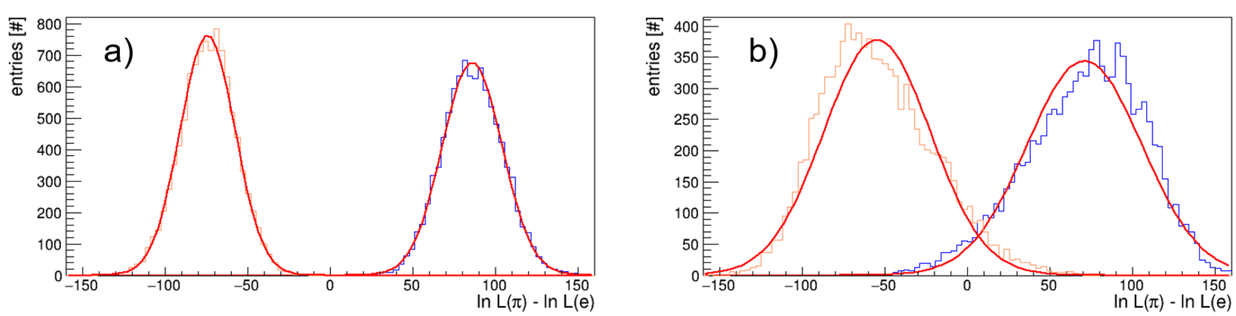

Figure 14: Simulated e/π performance of the hpDIRC at a momentum of 1 GeV/c and a polar angle of 30°, for an angular tracking resolution of 0.8 mrad. Log-likelihood difference for the Geant4 simulation without (a) and with (b) multiple scattering enabled. The corresponding e/π separation from the fits, ignoring non-Gaussian tails, is 9.2 s.d. without multiple scattering and 3.8 s.d. with multiple scattering enabled.

Figure 14 shows one preliminary result of our initial simulation study of the e/π performance of the generic hpDIRC design at a momentum of 1 GeV/c and a polar angle of 30°. The simulation was performed in the hpDIRC Geant4 software with multiple scattering either enabled or disabled. The angular resolution from the tracking system is simulated as 0.8 mrad, consistent with recent predictions for the EIC detector. The e/π separation power of the hpDIRC is dominated by the effect of multiple scattering, primarily inside the DIRC bar, limiting the separation to 3.8 s.d. and causing significant non-Gaussian tails in the log-likelihood difference distribution. This is just the first step into this study but, given the high interest from the EIC community, it is important to continue it to understand the hpDIRC capability for electron identification. Several aspects of this study also directly relate to the hpDIRC π/K performance at high momentum, in particular the application of a ring center fit to correct for a bias in the momentum vector and the integration of possible post-DIRC tracking information into the DIRC reconstruction to mitigate the effect of the non-Gaussian tails.

Alternative EIC DIRC Design Options In the previous FY we implemented initial versions of two alternative EIC DIRC options in our stand-alone Geant4 simulation package. The first one, known as the FDIRC option, is based on reusing the unmodified BaBar DIRC bar boxes, coupled via a transition prism to the solid fused silica expansion volume with cylindrical focusing. The dimensions of the focusing block were taken from the SuperB fDIRC design and will have to adjusted to the EIC phase space. The second newly implemented option is known as the Ultimate DIRC geometry, where the individual narrow bars are coupled to the expansion volume via a wide plate. This geometry has the potential to reach the best Cherenkov angle resolution by greatly reducing the effect of the bar width on the Cherenkov angle resolution.

Both newly implemented options will require optimization of the expansion volume shape and the readout resolution for the EIC phase space. This will be followed by a detailed mapping of the performance as a function of track polar angle and momentum. A comparison of these geometries to the other hpDIRC designs, including one based on wide plates instead of narrow bars, in terms of performance and cost will be important for the selection of the barrel PID system for the EIC.

Feasibility Study for a "Mini-DIRC" for Near-Beam Ion Identification The focus of the consortium is on PID in the central detector (including the endcaps), but identification of ions and ion fragments moving along the beam is also important for achieving key EIC physics goals, such as imaging of nuclear glue with thorough coherent diffraction with positive identification of light ions, and new topics such as discovery of rare isotopes produced in electron scattering on heavy-ions. The ions would be detected using a forward magnetic spectrometer, integrated with the accelerator, measuring the magnetic rigidity ($\propto$M/Z or A/Z) of the ions. However, a measurement of Z is also needed to independently extract both the mass A and charge Z of the ion independently. Since all ion fragments travel with essentially the same average velocity, TOF techniques are not ideal (in the EIC there is no need to use TOF for disentangling multiple vertices in a single bunch crossing as at the LHC). One possible approach is dE/dx, which is proportional to Z^2. This works well for light ions, and dE/dx could be measured by the Si-trackers in the Roman pots, but for heavy ions the amount of material needed to distinguish, Z=82 from Z=81 would be substantial. Thus, it is preferable to use a DIRC-like Cherenkov detector, which would offer a compact size, a large photon yield, and good timing resolution. The bar would be placed behind the last Si-tracker. The number of photons produced in fused silica is about 100 * Z^2 per mm. Most of them are lost, but 5 mm of fused silica should provide 100,000 useful photons. This is an order of magnitude more than is required to reach an uncertainty in Z^2 of 1% (Z=81 from Z=82 are separated by 2.5% in Z^2). The main R&D challenge is to find a readout for the thin bar which can count the photons with a precision of at least 1%.

2.4.4 Summary of FY21 Proposed Activities

Software

- Complete the prototype simulation, evaluate performance, and determine requirements for supplemental beamline instrumentation.
- Study the e/π separation as function of momentum.
- Compare the performance of different DIRC geometries.
- Optimization of design in coordination with the other eRD14 PID systems within full EIC central detector simulation framework.
- Study of feasibility of "mini-DIRC" for near-beam ion identification.
- Investigation of chromatic dispersion mitigation in the context of different photocathode materials and readout timing precision.
- Development of analytical version of time-based imaging.

Hardware

- Incremental upgrade of the prototype based on available components (sensors, readout electronics).
- Set up the prototype DAQ system and commission the PHOTONIS XP85012 MCP-PMTs with TRB/PADIWA-based readout electronics.
- Integrate small-pixel MCP-PMTs and Hawaii readout into prototype.
- Finalize the characterization of the new prototype lenses.
- Conclude the study of radiation hardness to gamma and neutrons.

2.4.5 hpDIRC FY21 R&D Deliverables

- Validation of prototype DAQ for PHOTONIS XP85012 MCP-PMT array with TRB/PADIWA-based readout electronics.
- Completion of Geant simulation package for the hpDIRC prototype in beam test environment.
- Performance evaluation of the three new prototype lenses in laser setup.
- Conclusion of radiation hardness study of candidate lens materials, including PbF_2 and sapphire, using both neutron and gamma sources.

- Cost/performance optimized hpDIRC design.
- Performance comparison of various EIC DIRC options.

3 Lepton (electron) Identification

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The focus of the funded activities of the eRD14 consortium is on hadron identification. However, we have not neglected electrons and muons. At an Electron-Ion Collider, detection and identification of the scattered electron is a critical requirement. Also, many important processes involve particle decays to leptons (e.g.$J/\psi \rightarrow e^+e^-$). The baseline system for e/π identification is the electromagnetic calorimeter (EMCal), which is included with 4π coverage in all EIC model detectors. However, the pion suppression achievable in the EMCal is limited by charge-exchange events ($\pi^- p$ to $\pi^0 n$), resulting in an electromagnetic shower indistinguishable from one initiated by an electron ($e - p$), and associated with a charged track. Although different types of EMCals have been considered for different parts of the EIC detectors, in general a good EMCal will provide e/π background suppression by up to about 1:100 for a single track, or 1:10^4 for dilepton production (e.g., J/ψ). This can be improved with a shower-shape analysis in a high-granularity EM calorimeter, but at the cost of a loss of electron efficiency. Fig. 15 illustrates the trade-off between PID detection efficiency vs. purity of PID, for a fixed PID separation of two species by Nσ. The inclusion of a hadronic calorimeter (HCal) behind the EMCal will only slightly improve the e/π identification, since charged pion events that charge-exchange in the EMCal will be mostly contained in the EMCal, and will not give large signals in the HCal. In order to reach kinematics where pion backgrounds are high, additional e/π ID detectors will be needed.

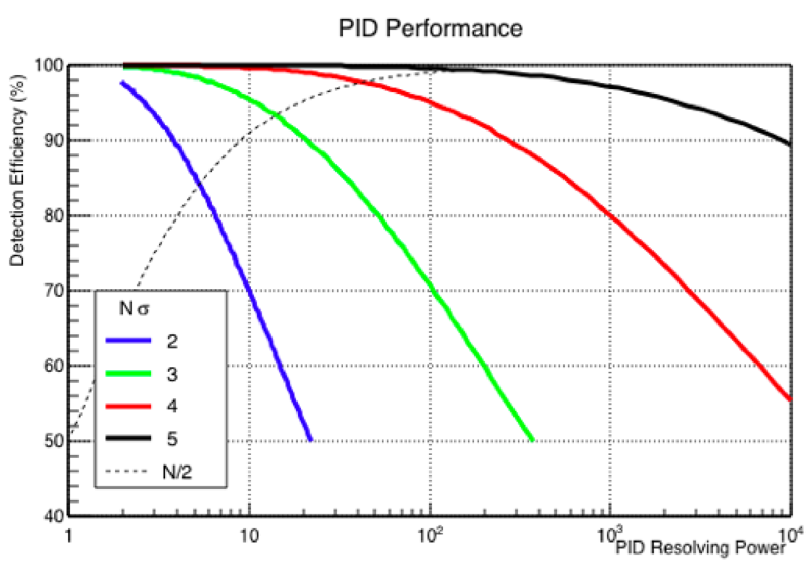

Figure 15: Contours of constant PID separation, Nσ, in the plane of PID efficiency vs. resolving power vis-a-vis the unwanted species. The dashed line corresponds to making the PID separation at the midpoint between the two particle-species distributions)

3.1 Electron ID

The twin roles for lepton ID (identification of the scattered electron and of leptonic decays of hadrons such as J/ψ) impose different requirements in terms of coverage in both momentum and angular range. The main challenge for the identification of the scattered electron comes from low-momentum (1 – 2 GeV) pions in the electron-side endcap and the central barrel. As shown in Fig. 17 and Fig. 16(left), this background rises rapidly at lower momenta, while the EMCal pion rejection factor is at best constant, and in reality likely to get slightly worse. However, the combination of an EMCal and a Cherenkov detector such as the mRICH or DIRC can offset the rise in pion background, making it possible to detect and identify scattered electrons with lower momenta, effectively extending the kinematic reach of the EIC.

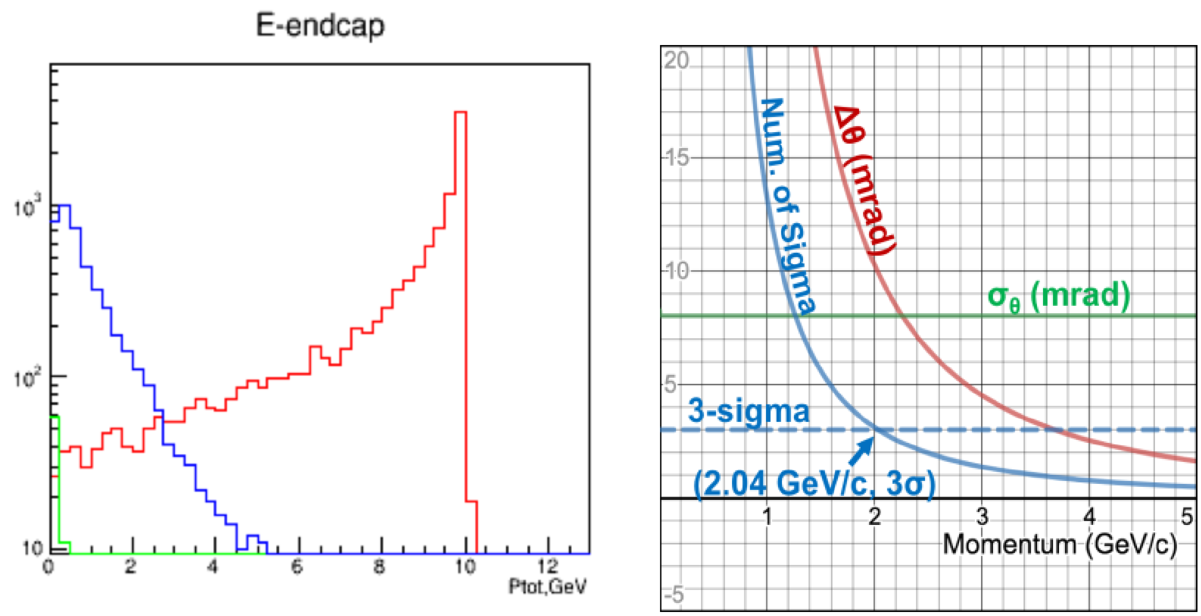

Figure 16: (Left) Electron-endcap momentum distributions of scattered electrons (red), negative pions (blue), and secondaries (green) for collisions of 10 GeV electrons on 100 GeV protons. (Right) The projected e/π separation of the mRICH detector.

If implemented in the electron endcap, the mRICH (see Section 2.3) will provide additional e/π discrimination, as illustrated in Fig. 16 (right). The right panel in Fig. 16 shows that while the additional e/π discrimination is 3σ at 2 GeV, it rises to 13-sigma at 1 GeV. Following the dashed line of Fig. 15, the combination of EMCal and mRICH can ensure less than 1% pion contamination in the electron sample over the entire momentum range of Fig. 16 (left). Fig. 17, similar to Fig. 16, shows the particle multiplicities in the negative pseudo-rapidity side (electron-endcap side) of the central barrel region. Below 2 GeV/c , e/π discrimination is again challenging.

In the barrel region, the hpDIRC is expected to contribute to low-momentum e/π separation with at least 3-4 s.d. separation power at 1 GeV/c. As described in Section 2.4, the study of the e/π performance in simulation is one of the activities proposed for FY21.

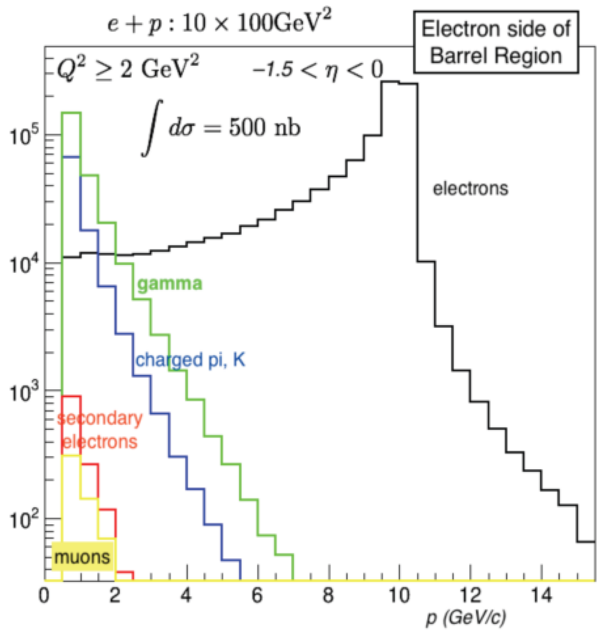

Figure 17: Central barrel region, negative-pseudorapidity (electron endcap side): momentum distributions of scattered electrons (black), photons from hadron decays (green), charged π/K (blue), electrons from hadron decays (red), and muons (yellow). The particles are produced in DIS of 10 GeV electrons colliding with 100 GeV/c protons. The events are selected for $Q^2 \geq 2$ GeV/c^2 .

In the hadron endcap, we have demonstrated in the past that the proposed dRICH provides $\geq 3\sigma$ e/π separation up to 19 GeV/c . For the C_2F_6 gas alone, $\geq 3\sigma$ e/π separation is achieved over the range 5–19 GeV/c . Thus, in the ion endcap, with the dual-RICH together with the EMCal, 10^3:1 e/π separation per track is achievable at ∼95% electron efficiency at 19 GeV, rapidly rising at lower momenta [10]. This is sufficient for identifying, for instance, decays of charmonium.

3.2 Muon ID

Muon identification is important for di-lepton production (both inclusive and vector meson decays, e.g. J/ψ) and for semi-leptonic decays of heavy-flavor hadrons. Every EIC detector concept includes some form of hadron calorimetry in the ion downstream endcap of the central detector. However, the different proposals differ significantly in the central barrel region. We are assessing the Belle (and its Belle-II upgrade) KLong – Muon (KLM) detector as a modest-cost option for instrumenting the solenoid return yoke. This has shown good performance for muon ID and modest performance for measuring the energy of high-energy neutrons and K-long mesons

4 Photosensors and Electronics

The specific requirements that the DIRC and the RICH detectors must fulfill within the scope of the EIC pose unique constraints on sensor and electronics performance different from any previous DIRC and/or RICH implementation. Table 1 below lists the minimum requirements on DIRC, mRICH, and dRICH photosensors. Specifically, the small pixel size of 2 – 3 mm and the immunity to magnetic fields of magnitude in the range 1.5 – 3 T are unique constraints. The main objective of this R&D effort during the proposed funding period is to identify and assess suitable photosensor

[10] For example, at 10 GeV/c, the dRICH itself provides a $10\sigma e/\pi$ separation.

and electronics solutions for the readout of the EIC Cherenkov detectors, both for the full EIC detector and for prototypes in beam tests. Depending on the evaluation outcome, design optimization studies of those photosensor and electronics parameters that are found lacking in the evaluated samples but critical for operations in the EIC environment, will be carried out. In addition to supporting the adaptation of developing photo-sensor technologies for the EIC Cherenkov detectors (such as LAPPDs and GEMs) the goal is to identify a cost-efficient common readout solution that is shared within the EIC-PID consortium. Ultimately, in the long term, this R&D work will allow us to make a recommendation about the best photo-sensors and electronics solutions for the PID detectors in EIC implementation.

Sensor requirements and options

The consideration of possible photosensor solutions for each detector component is driven by the operational parameters of the detector, with cost optimization in mind. Table 4.1 below summarizes the performance parameters that photosensors for the hpDIRC, mRICH, and dRICH must satisfy.

The key parameters of the photodetectors for the mRICH are small pixel size, resistance to magnetic field, and low cost (due to its large sensor area). Depending on the mRICH location, the requirement for radiation hardness will vary. The detector does not require good PMT timing resolution. GEMs with a photocathode sensitive to visible light, with their good radiation hardness and good position resolution, would be a very good and cost-effective solution for the mRICH. SiPMs could be used where their radiation hardness is sufficient. MCP-PMTs such as LAPPDs with pixelated readout could be considered as possible photosensors for mRICH detectors if they have sufficient resistance to magnetic fields. In the final EIC detector, it is possible to use different photosensors in different locations (LAPPDs could, for instance, be use near the beam where the radiation is high and SiPMs away from the beam, where the angle of the magnetic field changes more rapidly).

The key parameter of the photodetectors for the dRICH is the small pixel size. Although the relative sensor area (normalized to the absolute detector area) of this detector is small, due to the large absolute detector area, cost is also an important parameter. Good sensor options for the dRICH would be similar to the ones for mRICH (keeping in mind that due to the location of the sensors, the requirement for radiation hardness is not as important for the dRICH).

The key parameters of the photodetectors for a DIRC are fast timing, small pixel size, and a moderate to low dark count rate (DCR). Magnetic-field tolerance is required if the DIRC readout is located within the magnetic field of the solenoid. SiPMs might be possible to use for a DIRC if future developments lower their DCR to an acceptable level. Currently, the only photodetectors satisfying these requirements are MCP-PMTs (including LAPPDs with pixelated readout). Excellent timing resolution (100 ps RMS) is in particular required for the high-performance DIRC if a time-based PID reconstruction method is adopted for the geometry based on wide radiator plates. Such timing resolution is satisfied by currently commercially available MCP-PMTs, however, development of electronics with good time resolution for small signals may be required.

Parameter	hpDIRC	mRICH, dRICH
Gain	$\sim 10^6$	$\sim 10^6$
Timing Resolution	≤ 100 ps	≤ 800 ps
Pixel Size	2 – 3 mm	≤ 3 mm
Dark Noise	≤ 1 kHz/cm^2	≤ 1 MHz/cm^2
Radiation Hardness	Yes[11]	Yes
Single-photon mode operation?	Yes	Yes
Magnetic-field immunity?	Yes (1.5 – 3 T)	Yes (1.5 – 3 T)
Photon Detection Efficiency	$\geq 20\%$	$\geq 20\%$

Table 1: List of performance requirements for the photosensors for the EIC PID Cherenkov detectors. The EIC radiation levels can be inferred from current operations at RHIC, and will depend on the sensor location.

4.1 Sensors in High-B fields

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The integration of the three Cherenkov detectors in the central detector involves setting their photosensor readouts in the non-uniform fringe field of the solenoid. While an out-of-field readout option for the DIRC may be feasible, an in-field readout is the only option for the two RICH detectors. The objective of this activity, thus, has been to assess the gain and the timing performance of commercially-available photosensors in high magnetic fields (due to the maximum field of 5 T attainable by our magnet, we can do the assessment from 0 T up to the field magnitude at which the sensor performance breaks down) and for various relative orientations between the sensor and the magnetic field, and to reasonably support (as needed for the R&D) further design optimization studies of these sensors. The long-term goal of the research is to recommend sensor options for Cherenkov-detectors readout in the magnetic field of the solenoid magnet.

4.1.1 FY21 Proposed High-B R&D Activities

The focus of our work in for FY21 will be on (a) the detailed characterization of a new 10-μm multi-anode Planacon (XP85122-S, HiCE) in magnetic fields from 0 T up to the maximum field where the gain measurements show that the PMT performance breaks down, and (b) the detailed characterization of a 6-μm multi-anode Photek MCP PMT (MAPMT253) in magnetic fields from 0 T up to the maximum field where the gain measurements show that the PMT performance breaks down.

The first part of the proposed work is a delayed activity from FY20, due to travel suspensions and the closure of Jefferson Lab. We have purchased one unit Planacon, XP85122-S, HiCE. This unit has several improved characteristics that are relevant for the EIC-PID program, compared to the unit we tested in 2017 – 2019. The PMT has a smaller pixel size, which is critical for the validation of the hpDIRC prototype performance, and has an atomic-layer-deposition (ALD) photocathode that reduces ion-feedback. Tests performed by the PANDA DIRC group, however, suggest that the sensor has worse High-B immunity than its non-ALD counterpart. Given that XP85122-S is currently the only estabished MCP PMT with a pixel size that satisfies the requirements for the Cherenkov detectors, it is critical that its performance is mapped for a wide range of $(B, \theta, \phi, \mathrm{HV})$. This new Planacon MCP PMT will not only be used for evaluation in the High-B tests, but also, as part of the readout of the hpDIRC prototype and for the validation of the SiREAD readout of this type of PMT. In FY21, we will perform a full scan of the gain, efficiency, and timing as a function of $(B, \theta, \phi, \mathrm{HV})$. Here we do not request funds for this activity - we will be using the funds dedicated for these tests in the FY20 R&D budget. This test will be carried out in December 2020. In addition, we will also map the ion feedback of the sensor and the gain and the timing resolution as a function of the high voltages across the three internal stages, Photocathode – MCP1, MCP1 – MCP2, and MCP2 – Anode. This assessment will be carried out in Summer 2021.

The second part of the proposed work is a new activity that aims to evaluate the performance of a multi-anode Photek MCP PMT of 6-μm pore size. At this time, this is the only multi-anode MCP PMT on the market with a pore size smaller than 10 μm and the assessment of its performance in High-B fields is of great interest to the eRD14 program given that smaller pores typically lead to a wider High-B range of reasonable performance, *i.e.*, one expects that a 6-μm MCP PMT will be operational at higher B-field magnitudes than a 10-μm MCP PMT. As 3 T magnetic field is not excluded for the EIC detector, the Photek MCP PMT needs a comprehensive evaluation. One interesting aspect of such an evaluation is the gain dependence on the B-field magnitude at different sensor orientations relative to the direction of the field. For example, a single-anode 3-μm pore size Photek tube, that was tested under this R&D program in 2015, showed great performance up to 4 T at an angle $\theta = 0°$, whereas at any other angle, the B-field range of operation was much more limited. Given that some readout sensors for hpDIRC and mRICH detectors would have to be positioned at somewhat larger angles than $\theta = 0°$, the measurement of the sensor performance at different orientations is an important aspect of the proposed activity. In our setup, we collect and write permanently on disk a set of data for every $(B, \theta, \phi, \mathrm{HV})$ setting. The fADC records the waveform for every event. This allows us to extract later in the analysis, the gain, timing resolution, and efficiency for that setting from the same data set. The only parameter that needs a separate measurement is the ion feedback, which requires a different trigger.
We have negotiated with Photek to borrow, free of charge, a loaner 6-μm MCP PMT with a pixel size of $6{\times}6$ mm^2. We will have the tube over a very limited amount of time, a few weeks in December 2020, when we will measure its gain, timing resolution, and efficiency as a function of $(B, \theta, \phi, \mathrm{HV})$. Given the value of a 6-μm-pore-size multi-anode MCP PMT for the EIC-PID detectors, we propose to purchase one unit of Photek MAPMT253, which has a pixel size of $3{\times}3$ mm^2 for the purpose of the eRD14 program. This will allow us to do more detailed studies of the tube in B-fields: ion feedback and gain and the timing resolution as a function of the high voltages across the three internal stages, Photocathode – MCP1, MCP1 – MCP2, and MCP2 – Anode. This assessment will be carried out in Summer 2021.
After the Photek sensor is evaluated in the High-B facility, it will be shipped to Hawaii University to be equipped with a SiREAD-based readout electronics of all 256 channels so that the sensor and its electronics can be validated in the beam test of the hpDIRC prototype in FY22[12].

[12]For the purpose of the High-B evaluation, we typically readout up to only 4 PMT channels with a local custom

The studies of the ion feedback of the Photek and Photonis sensors will address the concern about the possible lifetime of the tubes if they are continuously operated close to their maximum allowed high voltage (which is typically done to compensate for the gain decrease with increasing B-field). The studies of the response of the sensors in B-fields for varying voltages of the internal stages will allow us to identify the best combination of voltages for most optimal performance in a given set of (B, θ, ϕ).

The High-B R&D program is being carried out primarily by the University of South Carolina (USC) and the Detector Group at Jefferson Lab. The main activity is the sensor(s) test with a cold magnet, which takes place in June – July every year over the period of three weeks [13]. During the three weeks, we take data continuously over 12 – 14 hours each day, by manning three four-hour long shifts with two people in each shift. This data taking is referred to as a run. USC is responsible for the planning, coordination, and running of the test activities, analysis of the collected data, and the requisition of sensors and necessary electronics modules. The Detector Group is responsible for the requisition of the cryogens for the magnet, the design and construction of the readout solution for each sensor and any initial bench tests. The two groups maintain and upgrade the High-B facility jointly. The man power required to carry out the sensor tests in High-B field in one run, is 6 persons each day. USC provides half of this personnel (one faculty, one graduate, and one undergraduate students). The other personnel includes our DIRC collaborators from CUA, SB, and former USC graduates who currently work at Jefferson Lab. Thanks to our optimized model of planning, the collaborative support from the DIRC group and JLab, the ability to maintain a continuous daily shift schedule, and the 3-week-long measurements, we are capable to complete comprehensive multi-parameter scans of 1 – 2 sensors in one run with a very modest budget.

The requested budget in the 100% scenario covers the cost of the cryogens to cool the magnet and operate it over 3 weeks of continuous measurements, of summer salary of one USC undergraduate, of small components, such as boards, holders, connectors, pre-amps, *etc.* to readout the sensors and operate them in the dark box, the cost of a 6-μm multi-anode Photek MCP PMT, and of travel of USC personnel to prepare for and perform the measurements and JLab. For FY21, the request for a summer salary of the USC undergraduate, Benjamin Moses, is only 50%. The other 50% will be covered by a USC research award, which Benjamin already won specifically for this project. The travel cost has been minimized by using car pooling and shared lodging for the students. We also benefit from a relatively low USC overhead of 26%, compared to the rates of 50% at other institutions. The cost of the Photek MCP PMT of $17.9k includes the quoted price of the sensor, South Carolina sales tax, and shipping; no overhead is budgeted for the sensor as it qualifies as a capital equipment. We do not request funds for technical staff support, such as engineering, magnet operations, or DAQ maintenance, all of which are provided by JLab free of charge to eRD14.

The 80% and 60% budgets are the same and contain the minimum budget to perform one test run. They do not include the cost of a Photek MCP PMT. This means that in the 80% and 60% scenario, we will not be able to comprehensively test the High-B performance of the 6-μm multi-

readout solution

[13] Due to COVID19, the 2020 test will be carried out over two weeks in December 2020.

anode Photek MCP PMT, characterize the sensor, and implement it in the hpDIRC prototype readout for the hpDIRC prototype beam test in 2022. This will have some negative ramifications for the TDR of both mRICH and hpDIRC in 2023, as the 6-μm MCP PMT is the only one on the market with such a small pore size and, therefore, is potentially the most promising readout candidate for mRICH and hpDIRC, especially, if the central solenoid of the EIC detector is chosen to have a central field larger than 1.5 T (the interest in higher fields has risen again recently and such an option is not excluded from current considerations). At the same time, it is a very novel sensor for Photek, and does not have yet an established track record. This makes it even more urgent to acquire one such tube in FY21 for EIC and implement it as soon as possible so its performance can be tracked over time in different configurations: in High-B, on a test bench, with a detector prototype, and in beam). From the point of view of the eRD14 program, the purchase of a 6-μm Photek tube in FY21 is well aligned in time with the activities on the hpDIRC prototype, the development and characterization of pixelated LAPPD, and the development of readout electronics for all Cherenkov prototypes based on SiREAD chips.

With the comprehensive High-B evaluation of the latest Photonis Planacon and the new 6-μm Photek MCP PMT, our program to identify MCP-PMT operational parameters that are optimized for application in the Cherenkov PID detectors in the high magnetic field of the central detector at EIC, will be completed. Beyond FY21, our effort will be focused on full-sensor characterization of LAPPDs, Photek, and Photonis MCP PMTs (such as quantum efficiency, cross talk, charge sharing, etc.) with the SiREAD-based readout electronics. To this effect, we plan to merge the High-B facility with the CLAS12/RICH facility at JLab and join efforts with INFN in performing an EIC-PID PMT (MCP PMT, LAPPD, and SiPM) characterization there for the EIC-PID detector TDRs.

4.1.2 FY21 High-B R&D Deliverables

- Report on multi-anode PMT (Planacon) performance as a function of $(B, \theta, \phi, \mathrm{HV})$.
- Report on Photek multi-anode PMT performance as a function of $(B, \theta, \phi, \mathrm{HV})$.
- Publication of the results of the above two measurements.

4.2 LAPPD$^{\mathrm{TM}}$ MCP-PMTs

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The LAPPD collaboration has successfully commercialized the standard new type MCP-PMT using the atomic layer deposition technique as LAPPD$^{\mathrm{TM}}$, with the same very high performance as existing MCP-PMTs, but at a significantly lower cost. The eRD14 MCP-PMT/LAPPD R&D activities aim to adapt the LAPPDs to the EIC-detector requirements, which include pixelated readout and acceptable performance in high magnetic fields. With these optimization, the LAPPDs can be used for the readout of DIRC, dRICH, and mRICH subsystems as well as for TOF applications.

The eRD14 MCP-PMT/LAPPD efforts in the past fiscal years, led by the ANL group, were focused on the development and proof-of-principle demonstration of an MCP-PMT design that has fine pixelation and magnetic-field tolerance. For this purpose, the ANL group produced several units of MCP PMTs using MCPs provided by the LAPPD commercial manufacturer (Incom, Inc.). The critical performance parameters of the ANL MCP-PMT design, obtained in bench tests of the latest unit, exhibit a magnetic field tolerance of 1.5 Tesla, RMS timing resolution of 83 ps, and position resolution of 1.0 mm with a pixel size of 3×3 mm^2. The ANL design parameters are being implemented by Incom, Inc. in their new generations of sensors, GEN-II LAPPD and GEN-III HRPPD. Details of these activities can be found in the progress reports.

FY20 oversees the transition of the eRD14 MCP-PMT/LAPPD R&D from generic MCP-PMT development into project-oriented evaluations of available LAPPDs with integrated designs, and preparation of LAPPDs for upcoming beam tests of various EIC-PID Cherenkov sub-systems. By the end of FY20, we will complete the fabrication of two 6×6 cm^2 fully-integrated ANL MCP-PMTs to conclude the proof-of-principle efforts.

Our activities in FY21 (see details in section 4.2.2 below) will focus on the validation of commercially available Incom Gen-II LAPPDs at Fermilab beamline in a highly-pixelated configuration, as well as on comprehensive tests with an mRICH prototype module. With the delivery of Gen-III HRPPD, tests on the bench and in magnetic field will also be performed. [14]. This timeline is well aligned with the accelerated CDR/TDR timeline for the EIC detector(s), which requires to demonstrate sub-system readiness by 2023, and the planned beam tests of mRICH, dRICH, and DIRC prototypes in 2021 and 2022.

4.2.1 Synergistic efforts at ANL supported by external funding

The synergistic efforts supported by ANL funding include the performance validation of LAPPDs in high background rate environment and design and simulation of a gaseous-RICH detector for TOPSiDE detector concept, as described in details below.

The SoLID experiment at Jefferson Lab will use a light gas Cherenkov detector as part of their trigger. Due to the very high luminosity of the experiment (10^{39} cm$^{-2}\cdot$s^{-1}), the expected single-photon background rate is extremely high. In synergy with the eRD14 MCP-PMT/LAPPD work, the ANL group has been working on LAPPD performance validation with the SoLID gas Cherenkov counter prototype at Jefferson lab. The purpose of the experiment is to test the performance of available LAPPDs in a high rate background open environment. The available Gen-I LAPPD with stripline readout is not optimized for EIC applications, so the tests will not address all critical performance parameters, however the high-rate aspect of the test will provide valuable information for EIC.

A Gen-I LAPPD from Incom was tested in the SoLID small Cherenkov telescope setup in Spring 2019 at JLab Hall C high background rate open environment. During the experiment, we

[14] Gen-III HRPPD is optimized for high-rate applications. It has a novel high-density pixelated co-fired anode allowing for a direct pixelated readout. Another important characteristic is its unobstructed field of view by spacers (as used in Gen-II LAPPDs). These features make the sensor a possible candidate for the hpDIRC readout.

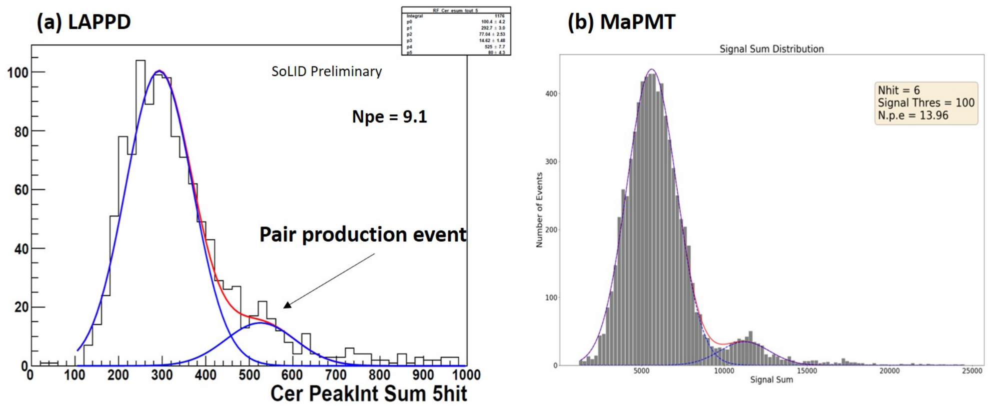

Figure 18: Distribution of Cherenkov event signal sum obtained from (a) LAPPD and (b) MaPMTs after the reduction of high rate background events with a timing cut and hitting pattern correlation. Both photosensors were able to separate the single events and pair production events.

used 8.1 GeV electron beam to hit the LN2 target, free electrons were scattered at all direction by the target. When a high energy particle (mainly scattered electron) traveled through the small Cherenkov telescope, which was filled with CO2 at atmospheric pressure as radiator medium, Cherenkov photons were emitted along the particle path. The Cherenkov photons were reflected onto photosensors (MaPMTs or LAPPD) by a flat mirror, while the particle continued traveling through the mirror and generated trigger signals in the scintillator and calorimeter to initiate the data acquisition.

Figure 18(a) shows the distribution of the Cherenkov event signal sum obtained from LAPPD after the reduction of high rate background events with a timing cut and hitting pattern correlation. The main single event peak and the following pair production peak are separated in the histogram, and the center value of the pair production peak is exactly twice that of the single event peak. The gaussian distribution of the main single event peak gives an experimental number of photoelectrons of 9.1 (Npe = 9.1). From the theoretical calculation, we expect a Npe value of 10.8 for this LAPPD in our setup. The experimental result agrees with our expectations. The MaPMT result is also plotted in Figure 18(b) for reference. The high QE (35%) and pixelated readout of MaPMTs provide them better performance on separating single events and pair production events. Considering the very low QE (7%) of the received LAPPD, the performance of LAPPD on single and pair production events separation in such a high rate background open environment is pretty encouraging.

A detailed simulation of the experiment was developed with the GEANT4 simulation toolkit to simulate the passage of particles, such as electrons and photons, through the prototype detector. The simulation also considered the refractivity of the corresponding medium, as well as the experimentally determined mirror reflectivity and quantum efficiency of photosensors. Figure 19a shows the geometrical setup and visualization of one Cherenkov event in our experiment with MaPMTs as the photosensors. It was found that with an additional mirror tilting angle of 15 degrees due to misalignment, the output from simulation describes the experimental data best. The simulation results strongly support our findings in the data analysis for the experiment.

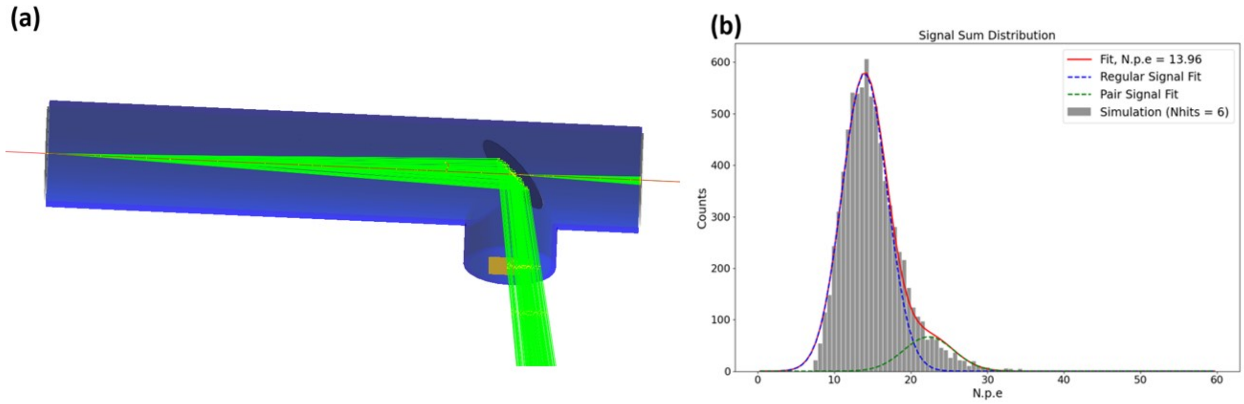

Figure 19: (a) Geometrical setup and visualization of one Cherenkov event in the simulation. The MaPMT array is shown as a golden piece in the plot. In this event visualization, an incoming electron (red track) generates multiple optical photons (green tracks) through the Cherenkov process in the CO2 gas. (b) Simulation result for distribution of Cherenkov event signal sum obtained from MaPMTs, the simulated distribution well describes our experiment results with a 15 degree misaligned mirror.

With the approval of SoLID pre-R&D and the availability of a Gen-II LAPPD (#38) from Incom, we prepared a test of this LAPPD with capacitively coupled readout using the full-scale Telescopic Cherenkov Device (TCD) at JLab Hall C in Spring 2020. Argonne group had the GEN II-LAPPD attached to an 8×8 array 25×25 mm^2 pixel electronic board, which is the same pixel size as the MaPMT quadrants designed for SoLID Cherenkov counter. A p-terphenyl wavelength shifter was coated on the LAPPD borofloat glass entrance window to enhance the Cherenkov detection range down to 200 nm. The LAPPD was later installed in the LAPPD housing with all electronics connected at JLab and stored at JLab before the COVID-19 pandemic. The Gen-II LAPPD is currently ready to be swapped with MaPMTs for beamline testing once JLab reopens.

The TOPSiDE (Timing Optimized Pid Silicon DEtector) concept defines a boundary in the forward hadron direction where additional PID detectors are needed, and in this case, we use a ring imaging Cherenkov detector for high momentum hadron particle identification. Supported under Argonne LDRD, significant progress in detector simulations has been achieved. For the TOPSiDE RICH, a generic RICH detector with full optical photon simulation and the pixelized readout was developed, as shown in Figure 20. Future work aims to further optimize the gaseous-RICH design and integrate low-cost LAPPDs as its photosensors. A prototype will be constructed to validate the gaserous-RICH performance for high momentum hadron particle identification.

4.2.2 FY21 Proposed MCP-PMT/LAPPD R&D Activities

With the announcement of EIC CD0 and a tight timeline to achieve CDR in 2 years and TDR in 4 years, we accelerated our progress on commercial LAPPD performance validation. We are expected to receive from Incom two Gen II LAPPDs in 2020 to prepare for Fermilab beamline Spring 2021 test, one Gen II LAPPD integrated with ANL design for magnetic field validation and one Gen III HRPPD (expected in May 2021) for hpDIRC Spring 2022 beamline test. We expect

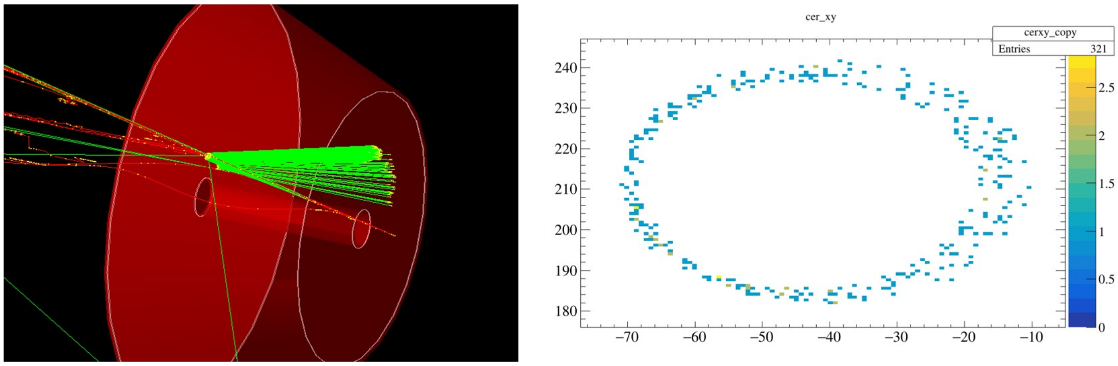

Figure 20: The simulation of a simple generic gaseous RICH detector consisting of a plane mirror and opposing photon detectors (left). The distribution of Cherenkov photons on the photodetector show the shape of a cone (right).

the optimized Gen-II LAPPD to be a photosensor candidate for mRICH and dRICH, while Gen-III HRPPD (higher cost) to be a candidate for hpDIRC.

The proposed tasks will focus on detailed evaluations of these LAPPDs on bench, in magnetic field, and at Fermilab beamline. Bench tests will be performed in labs occasionally as device delivers.

Fermilab beamline test in Spring 2021 will be a combination of multiple experiments including performance validation of advanced 6-cm ANL MCP-PMTs, performance validation of Gen-II LAPPDs, and a newly proposed mRICH-LAPPD-TOF experiment. This is a combined effort of eRD14 (MCP-PMT/LAPPD and mRICH groups) and eRD6 (MPGD group). The focus of the MCP-PMT/LAPPD group is the performance validation of advanced ANL MCP PMTs and LAPPDs with simple pad pixel readout in the beamline, the focus of the eRD6 MPGD group is the application of novel zigzag readout with advanced MCP-PMTs and LAPPDs. With the available mRICH module, LAPPD photosensor, and readout, the three groups developed a plan to use the mRICH module as the first detector system for an mRICH-LAPPD-TOF beamline test in Spring 2021. We aim to verify that LAPPD could provide good position resolution with proton beam, and thus better Cherenkov angle resolution. If the beamline test is approved, we will also test the LAPPD performance with pion and kaon beams. The mRICH-LAPPD-TOF test will use the same GEM tracker as we set up for the MCP-PMT/LAPPD performance test. The combined Spring 2021 beamline experiments aim to achieve maximum R&D results with one beamline setup installation.

Magnetic field tests using ANL g-2 magnet facility will be performed to have the optimized Gen-II and Gen-III LAPPDs tested, including magnetic field dependence and angle dependence.

With previously produced MCP-PMTs at ANL using different ALD coatings, some MCP-PMT principle R&D will also be performed to study the dependence of MCP-PMT performance in the magnetic field on ALD coatings. Afterpulse and ion feedback with different ALD coatings will also be studied.

Depending on the electronics readout chips development, integration work of MCP-PMT/Gen II LAPPD with pixel readout and Hawaii SiREAD electronics will also be performed.

MCP-PMT/LAPPD bench, beamline and magentic field test:

- Full bench test of received Gen-II LAPPDs and Gen-III HRPPDs.
- In beam performance validation of Gen-II LAPPDs and ANL MCP-PMTs with simple pixel readout at Fermilab test beam facility (work with eRD6 MPGD group, the zigzag readout is eRD6 focus).
- mRICH-LAPPD-ToF experiment for combined RICH and TOF test with LAPPD (work with mRICH group and eRD6 MPGD group).
- Magnetic field test of an optimized Gen-II LAPPD and one Gen-III HRPPD.
- Possible integration of Gen-II LAPPD with an external pixelated anode and Hawaii SiREAD electronics (if available).

MCP-PMT principle R&D:

- Gain dependence in magnetic field study on ALD coating.
- MCP-PMT/LAPPD after pulse and ion feedback study.

4.2.3 FY21 MCP-PMT/LAPPD R&D Deliverables

- Publication on the performance of Gen-II, -III LAPPDs results from bench tests, in magnetic field, and in beam.
- Publication of the effect of ALD coatings on device performance in magnetic field, after pulse and ion feedback.

4.3 Readout Electronics for Detector Prototypes

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The development of advanced, high-performance RICH and DIRC detectors poses new demands on photosensors and requires new readout electronics. All eRD14 Cherenkov systems envision using small pixels (2–3 mm), while the DIRC also needs to obtain good timing (< 100 ps RMS) with the relatively small pulses produced by MCP-PMTs. While initial prototype tests have been made with larger pixels and poorer timing to validate Monte Carlo simulations, which were then used to infer the performance of the systems developed for the EIC, a future prototype will have to be able to directly demonstrate the desired PID performance. To achieve this, new readout electronics has to be developed. Our path forward remains based upon waveform-sampling methods, which we believe provide important in-situ diagnostic and performance benefits. At the same we acknowledge the recent development effort on the FastIC + picoTDC chipset. Such a system would, however, not be able to diagnose issues being seen with MCP-PMT operation in Belle II. Moreover, experience with the HPTDC (picoTDC predecessor) firmware development implies a significant amount of work will be needed to implement picoTDC readout for an EIC application.

The fast, waveform-sampling electronics being developed could in principle be used for all Cherenkov detectors. However, during the R&D phase they will, due to funding limitations, not be immediately available for all detector and photosensor combinations. In particular, the current priority is to first provide support for relevant MCP-PMT models, and later on expand this to SiPMs. During an early stage of the R&D phase, a demonstration of the PID performance for the two RICH detectors can be achieved using simpler MaPMTs and SiPMs that are supported by legacy electronics. But it is also important to develop the capability to test alternative sensor solutions and readout architectures to support both the ongoing R&D and as a fallback plan. The ALCOR chip under study for the SiPM irradiation program is an example of modern ToT-based readout that might eventually evolve following the Consortium needs. The chip features low-power TDCs of 50 ps time binning and high-rate capability, and a matrix pin layout compatible with bump-bonding for compact layouts.

To address the slightly different requirements and timelines of the various systems, we have developed a common consortium-wide strategy that provides a complete solution while maximizing synergies and minimizing cost. The Hawaii group has taken the main responsibility for the development of the front-end electronics (ASICs and boards), while INFN, together with JLab, has the lead on integration for both the sensors and back-end/DAQ. The development has been staged, from almost ready-to-go systems to provide a reliable reference based on a consolidated technology to innovative solutions optimized for the EIC prototypes.

For the front end, the older MAROC-based system that was used in the first mRICH test beam has been adapted for sensors (MAPMTs, SiPMs) with smaller pixels. It provides a reference readout system and a fallback solution. The new front-end that is being developed is based on the waveform sampling low-power, higher-performance ASICs, such as SiREAD, which are integrated on boards directly matching the footprint of the sensors. In contrast to MAROC, SiREAD also provides the high-resolution timing required by the hpDIRC for their time-based reconstruction algorithms. Nalu Scientific, LLC, a Hawaii-based small business specializing in System-on-Chips for particle physics, in collaboration with the University of Hawaii, produced a readout demonstrator based on the prototype 32 channel SiREAD chip.

Highly integrated, low-power, and high-performance readout of 256-anode, 50-mm photosensors is being studied at the University of Hawaii, which has extensive experience in developing electronics for modern PID systems, such as the Belle II TOP DIRC. The proposed system can be adapted to read out all the photosensors (MaPMT, MCP-PMT, SiPM) that are being considered for the various RICH and DIRC detector prototypes developed by eRD14. A compact board stack mates in the envelope directly behind the photosensors, permitting seamlessly abutting together an array of such devices. Each board stack consists of an interface board, which mates directly to the photodetector high-density signal connectors and hosts the waveform sampling ASICs, as well as a digital interface node. A simple and standard power and serial interface allows groups of these 256-anode devices to be collected into a single ethernet acquisition node.

A number of lessons have been learned in the design of the board and mating to the prototype SiREAD ASIC. These will feed-forward into the next generation of readout boards, and have already influenced the design of an improved readout ASIC. After completion of firmware integration, system performance evaluation will further inform the next generation development. Specifically, to further reduce cost and further integration, compactness and reliability the next stage of development will implement the follow-on to the SiREAD ASIC, the High Density digitizer System on a Chip (HDSoC). Moving from the prototype to the production ASIC is a natural step since the former will not enter volume production, and the transition does not incur additional costs.

HDSoC Parameter	Specifications
Channels	64
Sampling rate	1-2 GSa/s
Storage samples/ch	4096
Analog Bandwidth	0.7-1.1 GHz
RMS Voltage Noise	<1mV
Dynamic Range	10-11 bits
Signal Voltage range	2.1 V
ADC on Chip	12-bits
Feature extraction	on chip
Readout	Serial LVDS
Power Consumption	20-40 mW/ch

Table 2: HDSoC specifications.

In addition to increasing channel density from 32 to 64 channels, most of the state-machine control infrastructure provided by the companion FPGA will be integrated as "system on chip" functionality. In addition to built-in amplifier and biasing stages making it especially suitable for SiPM readout, built-in calibration and feature extraction circuitry greatly simplifies use. Such a high level of integration significantly reduces the digital interconnection burden and will make the system more scalable and make better utilization of a reduced number of gigabit fiber optic links used for control and data acquisition. Details of the HDSoC are provided in Table 2. For the programmable logic upgrade, we plan to use an FPGA capable of supporting the high-speed serial interface control and readout of numerous HDSoCs.

The large number of sensor's channels to be readout requires a compact, modular, and fast data acquisition system (DAQ). In addition, DAQ needs to provide single-channel timing information ($\sim$ few hundreds ps resolution or better) and possibly charge information (the smaller gas rings in dRICH, for example, show a simulated photon multiplicity on a single pixel of approx. 1.3). The SiREAD chip will be readout by a proper porting of the DAQ system already developed for the CLAS12/RICH, and based on a powerful optical link between the generic programmable FPGA front-end board and the VSX sub-system processor back-end board. This synergy would speed up the effort and simultaneously reduce development costs.

The electronics based on the MAROC chip and developed for CLAS12 has been designed to work at the single-photon level and to readout MAPMTs, but is compatible with SiPMs. Its modular design can be adapted to different sensor sizes, pixelization and types and will be maintained to serve as a reference readout system for the Consortium. In order to be able to readout several sensors during the past mRICH prototype beam tests, both a stand-alone TCP/IP direct link to a desktop and a complete CLAS12 DAQ VSX/VME chain, using the JLab SSP protocol, were successfully operated with a dedicated stand-alone data acquisition software.

We are in the process of making such an SSP-protocol based DAQ compatible with the SiREAD electronics. A preliminary positive assessment of the SSP DAQ firmware compatibility has been performed by the Hawaii group. Being designed to serve a complete detector, such a DAQ system is suitable for EIC, but represents an over-sophisticated and costly solution, especially during the prototyping phase. The INFN and JLab groups aim to realize a simplified version to be distributed among the Consortium groups based on the developments ongoing at JLab. A system has been realized initially for plant PET applications where one or more Ethernet Trigger Supervisor (ETS) connects several flash-ADCs (16-channel units of 250-MHz Analog to Digital Converters - EFADC), see Fig. 21. The functionality and operation of the ETS are both fully programmable to support other modules beside the flash-ADC. As a general feature, the ETS can support up to 8 front-end units located up to hundreds of feet away with connections via either copper or fiber of up to 5 Gbits serial link, and 1 Gbit Ethernet connection to the readout PC. When connected to other ETS, a master ETS can support up to 64 front-end units and features a programmable coincidence-matrix self-triggering capability. As a consequence, ETS lends itself to a streaming concept where specific windows of data for the streams are self-triggered and selected. The ETS was awarded a USA patent [15].

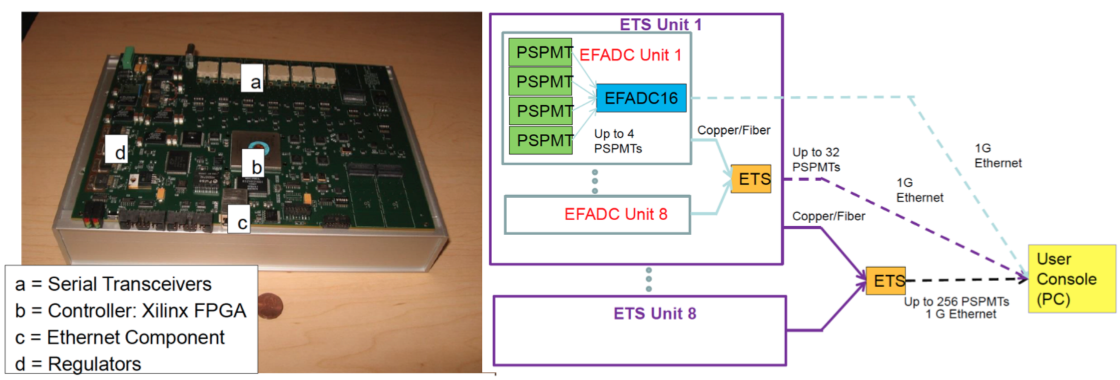

Figure 21: ETS board (left) and readout scheme developed for plant PET applications, where a ETS net connects up to 256 position sensitive photo-multipliers PSPMT (right).

The characterization of the readout solutions with standard and innovative sensors requires a benchmark assessment that is most effectively obtained on laboratory test benches. To this end, the INFN group intends to complete and maintain two permanent stations with a pico-second pulsed laser working in a single-photon regime and a complete readout chains, one in the U.S. (JLab) and one in Europe. The stations will be used to validate the different DAQ architectures, characterize and compare the alternative readout performance in conjunction with various photosensors, and

[15] https://www.osti.gov/doepatents/biblio/1463908.

to study readout solutions for sensors of various levels of irradiation with and without mitigation measures (*e.g.*, cooling and annealing).

The main INFN effort in the electronics activity in FY21 is the development of a portable DAQ system compatible with the SiREAD front-end operation. The requested budget for this effort is for manpower ($20k), materials ($13k) and travel for tests planned at JLab ($2k). It covers the adaptation of the existing DAQ solutions (SSP/VSX and ETS) to the Consortium needs and ensures the availability of a dedicated and flexible DAQ solution over the extended EIC R&D time period. It also covers the maintenance of the DAQ system for the reference electronics and the completion and maintenance of the test-bench laser stations.

4.3.1 FY21 Readout Electronics Proposed R&D Activities

- Complete SiREAD-based readout firmware integration with the SCROD FPGA
- Finish second generation firmware development for improved data throughput and front-end to back-end communication.
- Integration of the SSP DAQ protocol with the SiREAD front-end chips.
- Begin design of photosensor-integral HDSoC ASIC readout.
- Development of a portable DAQ system derived from the CLAS12 RICH readout.
- Maintenance and operation of reference electronics and pulsed-laser test stations.

5 Budget

5.1 Budget Request

As our baseline (100% level), we request $577.8k for FY21, but also provide budgets reduced by 20% and 40%, labelled “80%” and “60%, respectively, in the tables below. The budget request is lower than the one presented in the committee’s ”TDR readiness in four years” review in the Fall of 2019 due to the guidance that the overall R&D budget for the program would not increase significantly in FY21. However, this means that major hardware procurement, such as a full set of photosensors for the DIRC prototype, had to be shifted into FY22. The consortium strategy still provides a path to TDR readiness in four years, despite limited budgets and delays due to COVID-19, but this assumes that the FY21 proposal can be funded at a reasonable level and that more funding can become available in FY22.
All budget items include overhead at the receiving institution. Breakdown of the request by project and institution can be found below for all three funding levels. The consortium funds have been distributed among participating institutions so as to minimize overhead and maximize flexibility. The SOWs will be submitted with wording reflecting the possibility for institutions to fund collaborators at other institutions, for instance to cover travel costs.

5.2 Dual-Radiator RICH (dRICH)

Table 3 summarizes the budget required for dRICH project.

	100%	80%	60%
Postdoc, INFN/JLAB, 2 months (Luca Barion)	$6k	$6k	$6k
Postdoc, INFN/JLAB, 6 months (Aram Movsisyan)	$20k	$20k	$12k
Technical personnel, 6 months	$20k	$20k	$20k
Prototype Components	$22k	$10k	$5k
Travel	$6k	$2k	$2k
Total	$74k	$58k	$45k

Table 3: Budget for Dual Radiator RICH.

5.3 Modular Aerogel RICH (mRICH)

Table 4 summarizes the budget required for mRICH project.

	100%	80%	60%
Postdoc, INFN/JLAB, 2 months (Luca Barion)	\$7k	\$7k	\$7k
Postdoc, INFN/JLAB, 2 months (Aram Movsisyan)	\$5k	\$3k	\$2k
Postdoc, GSU (Deepali Sharma), 50%	\$27.3k	\$20.5k	\$13.7k
Grad Student, GSU	\$32k	\$27.3k	\$19.8k
Materials, GSU	\$4.5k	\$1.5k	\$1.5k
Travel and Conference Fee, INFN/GSU	\$10k	\$9k	\$7.5k
Total	\$85.8k	\$68.3k	\$51.5k

Table 4: Budget for modular Aerogel RICH.

5.4 High Performance DIRC (hpDIRC)

Table 5 summarizes the budget required for the hpDIRC project.

	100%	80%	60%
Postdoc, CUA, 50%	\$60k	\$60k	\$60k
Small-Pixel MCP-PMT Sensors	\$40k	\$20k	\$0
Prototype Evaluation (Travel, CUA)	\$15k	\$15k	\$15k
Prototype Equipment	\$5k	\$5k	\$2k
Radiation Hardness test	\$1k	\$1k	\$1k
Travel, CUA/GSI	\$9k	\$9k	\$6k
Total	\$130k	\$110k	\$84k

Table 5: Budget for High-Performance DIRC.

5.5 Sensors in High B-Field

Table 6 summarizes the budget required for the High-B project.

	100%	80%	60%
LHe and materials for high-B run, JLab	\$9.7k	\$9.7k	\$9.7k
Undergraduate student, USC (50% salary)	\$2.4k	\$2.4k	\$2.4k
Travel, USC	\$15.0k	\$15.0k	\$15.0k
Photek MCP PMT 6 μm pore size, $3\times$ 3 mm^2 pixel	\$17.9k	\$17.9k	\$0k
Total	\$45.0k	\$45.0k	\$27.1k

Table 6: Budget for Sensors in High B-Field.

5.6 ANL MCP-PMT/LAPPD

Table 7 summarizes the budget required for the ANL MCP-PMT/LAPPD project.

	100%	80%	60%
Staff effort for LAPPD bench test, beamline preparation and test	$30k	$27k	$25k
Materials for LAPPD bench test, beamline preparation and test	$10k	$10k	$10k
Staff effort for LAPPD magnetic field preparation and test	$15k	$13k	$10k
Materials for LAPPD magnetic field preparation and test	$5k	$5k	$5k
Argonne associate effort for magnetic field, principle R&D study	$25k	$15k	$0
BNL travel to Fermilab beamline test, Incom	$17k	$15k	$15k
ANL Travel to Incom, meetings	$5k	$5k	$5k
Total	$110k	$90k	$70k

Table 7: Budget for ANL MCP-PMT/LAPPD.

5.7 Readout Electronics for Detector Prototypes

Table 8 summarizes the budget required for the Readout Electronics project.

	100%	80%	60%
Postdoc, Hawaii, 12 months (Shivang Tripathi)	$60k	$60k	$58.8k
Grad Student, Hawaii, 0-9 months (Ethan Lee)	$38k	$15k	
Postdoc, INFN, 2 month (Luca Barion)	$7k	$7k	$7k
Postdoc, INFN, 4 month (Aram Movsisyan)	$13k	$13k	$13k
Components, INFN	$13k	$5k	
Travel INFN	$2k	$2k	
Total	$133k	$102k	$78.8k

Table 8: Budget for Readout Electronics for Detector Prototypes.

Please note that U. Hawaii negotiated a special arrangement for the postdoc position, which is exempt from indirect costs, making it possible to provide support for 12 months at the cost of 6.

5.8 Budget by Project and by Institution

Table 9 and Table 10 summarize the budget according to each project and each institution, respectively.

Project	100%	80%	60%
dRICH	\$74k	\$58k	\$45k
mRICH	\$85.8k	\$68.3k	\$51.5k
hpDIRC	\$130k	\$110k	\$84k
high-B	\$45k	\$45k	\$27.1k
MCP-PMT/LAPPD	\$110k	\$90k	\$70k
Electronics	\$133k	\$102k	\$78.8k
Total	\$577.8k	\$473.3k	\$356.4k

Table 9: Budget distribution by project.

Institution	100%	80%	60%
ANL	\$93k	\$75k	\$55k
BNL	\$17k	\$15k	\$15k
INFN	\$126k	\$99.5k	\$77k
CUA (and GSI)	\$130k	\$110k	\$84k
GSU	\$68.8k	\$53.8k	\$39.5k
U. Hawaii	\$98k	\$75.0k	\$58.8k
JLab	\$9.7k	\$9.7k	\$9.7k
USC	\$35.3k	\$35.3k	\$17.4k
Total	\$577.8k	\$473.3k	\$356.4k

Table 10: Budget distribution to each institution.